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ABSTRACT

A large portion of the paved highways in the United States are located in regions which experience freezing temperatures. It is well known that under extremely cold temperatures asphalt concrete pavements will undergo thermal stresses sometimes resulting in thermal cracking. An asphalt pavement that has developed thermal cracks in its wearing surface will experience a reduction in service life precipitating higher maintenance and rehabilitation costs. Therefore, one method of providing better quality highways at a reduced cost is to design asphalt pavements that can resist thermal cracking. In an attempt to further characterize the effects of cold temperatures on asphalt pavement the Federal Highway Administration (FHWA) authorized the construction of WesTrack. WesTrack is the FHWA's newest pavement testing facility located outside Reno, Nevada. The primary purpose of WesTrack is to serve as a working field laboratory for the development of Performance-Related Specifications (PRS). A secondary purpose of WesTrack is to serve as field validation of Superpave mix design and performance prediction concepts. It is anticipated that Superpave will provide a more reliable method of binder selection and minimize thermal cracking of asphalt concrete pavement.

This study was designed to assess the low temperature cracking potential of WESTRACK materials and relate this potential to binder content, air void content, material passing the #200 sieve, and age-conditioning. Samples were made for Thermal Stress Restrained Specimen Testing (TSRST) using three different modes, Field Mixed Field Compacted (FMFC), Field Mixed Lab Compacted (FMLC), and Lab Mixed Lab

Compacted (LMLC). In each case, multiple samples were fabricated to match the various mix designs tested in the WesTrack experiment. Variables for each mix design included aggregate gradation, asphalt content, and in place air voids. Following sample preparation, a number of samples from each design were either short-term and long-term aged or simply short-term aged. Each sample was then destructively tested in the TSRST apparatus to determine cold temperature cracking characteristics.

The results of this study suggest that the mix parameters asphalt content, air void content, and aggregate gradation have little effect on the low temperature cracking potential of WesTrack materials. Design for low temperature cracking is best addressed with proper performance graded binder selection.

The multiple regression fracture temperature prediction model constructed using the results of this experiment proved to be statistically insignificant and was therefore regarded as unusable. Due to this, the primary distresses likely to be addressed in a performance related specification are permanent deformation and fatigue cracking.

CHARACTERIZATION OF LOW TEMPERATURE CRACKING POTENTIAL FOR WESTRACK PAVING MATERIALS

by

Thomas J. Walker

A Project Submitted to

Oregon State University

In partial fulfillment of the
requirements for the degree of

Master of Science

ABSTRACT

A large portion of the paved highways in the United States are located in regions which experience freezing temperatures. It is well known that under extremely cold temperatures asphalt concrete pavements will undergo thermal stresses sometimes resulting in thermal cracking. An asphalt pavement that has developed thermal cracks in its wearing surface will experience a reduction in service life precipitating higher maintenance and rehabilitation costs. Therefore, one method of providing better quality highways at a reduced cost is to design asphalt pavements that can resist thermal cracking. In an attempt to further characterize the effects of cold temperatures on asphalt pavement the Federal Highway Administration (FHWA) authorized the construction of WesTrack. WesTrack is the FHWA's newest pavement testing facility located outside Reno, Nevada. The primary purpose of WesTrack is to serve as a working field laboratory for the development of Performance-Related Specifications (PRS). A secondary purpose of WesTrack is to serve as field validation of Superpave mix design and performance prediction concepts. It is anticipated that Superpave will provide a more reliable method of binder selection and minimize thermal cracking of asphalt concrete pavement.

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Master of Science project of Thomas J. Walker presented on December 14, 1998

APPROVED:

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I understand that me project will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my project to any reader upon request.

Thomas J. Walker, Author

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1.0 INTRODUCTION

Regions of the world that experience freezing temperatures spend millions of dollars annually repairing and maintaining asphalt concrete pavements that have failed due to low temperature cracking. In the United States where approximately 94% of the roads are paved with asphalt this mode of failure not only devours tax dollars, but results in direct costs to the public through delay costs, equipment costs, fuel costs, etc.

With a drop in temperature all asphalt pavements will undergo some degree of thermal contraction depending upon the physical properties of the two main components, aggregate and asphalt cement. As both aggregate and asphalt cool, tensile stresses develop within a pavement due to frictional resistance from the underling base course. While the temperature of an asphalt cement remains relatively warm (greater than 0° C), it will behave as a visco-elastic fluid thus dissipating thermal stresses by stress relaxation. However, at lower temperatures asphalt cement becomes brittle behaving more like an elastic solid. At these temperatures thermal stresses will continue to increase until the fracture strength of the asphalt cement is surpassed. When this occurs, physical cracking will appear on the surface of the pavement.

A challenge of the civil engineer is to design a hot mix asphalt (HMA) that has the ability to withstand extreme cold temperatures with out developing thermal cracks. To accomplish this in any region or climate, the effects of various construction techniques and available materials on low temperature cracking must be understood. One purpose of the Federal Highway Administration funded WesTrack program, and the primary focus of this study, was to quantify the effects asphalt concrete mix parameters have on low temperature cracking for use in a performance related specification.

1.1 Superpave Background

Superpave is a method of asphalt concrete mix design based on the physical properties of both asphalt cement and mineral aggregate. The development of Superpave began in 1987 as a result of the Strategic Highway Research Program (SHRP). (1) Superpave was designed to replace current empirically based methods of mix design with a scientifically based performance related method. The underlying premise of the Superpave method is that through proper selection and proportioning of paving materials a superior performing mix can be achieved. (1)

The Superpave method of mix design is performed in 4 major steps. First, mix components are selected based on expected traffic, environmental conditions of the paving site, and availability. (2) This is an extremely important step when designing for low temperature cracking, since the temperature at which a pavement becomes susceptible to low temperature cracking depends heavily on the binder. Second, the design aggregate structure is selected after comparing available aggregate gradations with predetermined aggregate specifications from the Superpave method. (2) Third, the optimum asphalt binder content is selected after compaction and analysis of at least 4 mixes with varying asphalt contents on the high and low side of an assumed initial optimum. (2) Fourth and finally, the resulting mix from the 3 steps above is subjected to moisture sensitivity testing to determine if this type of distress poses a significant threat to the in-place mix. (2)

Superpave is different from other design methods such the Marshall or the Hveem methods when accounting for temperature induced failures in that the binder specification

requires a dual temperature performance rating. Binders are specified as performance grade (PG) 64-22 for example. The first number is the high temperature in degrees C at which this particular binder retains sufficient physical properties for use in a pavement structure. (2) The second number in the designation is, similarly, the low temperature in degrees C at which the binder remains fit for use. (2) By determining the lowest and highest expected temperatures on a given job site and matching these temperatures with a particular PG binder many temperature related failures can be avoided. This method of binder specification has obvious advantages over former methods of binder selection which did not account for material behavior at high and low temperatures. When designing HMA for use in regions which experience low temperatures the Superpave method of binder selection is the first and most important step in preventing low temperature cracking. As stated earlier, this study will attempt to take Superpave one step further and determine how mix parameters and construction methods affect low temperature cracking performance.

1.2 WesTrack Background

WesTrack is an accelerated pavement research facility funded by the U.S. Department of Transportation's Federal Highway Administration. It is located in the high desert approximately 100-km southeast of Reno Nevada in the Carson River valley (Temperature range of approximately 40° C to -25° C). (3) The WesTrack project was constructed and operated beginning in 1994 by a group of 4 private companies in cooperation with 3 universities. The test site consists of an oval asphalt track approximately 2700 meters long with 26 HMA test sections. Each test section is 70

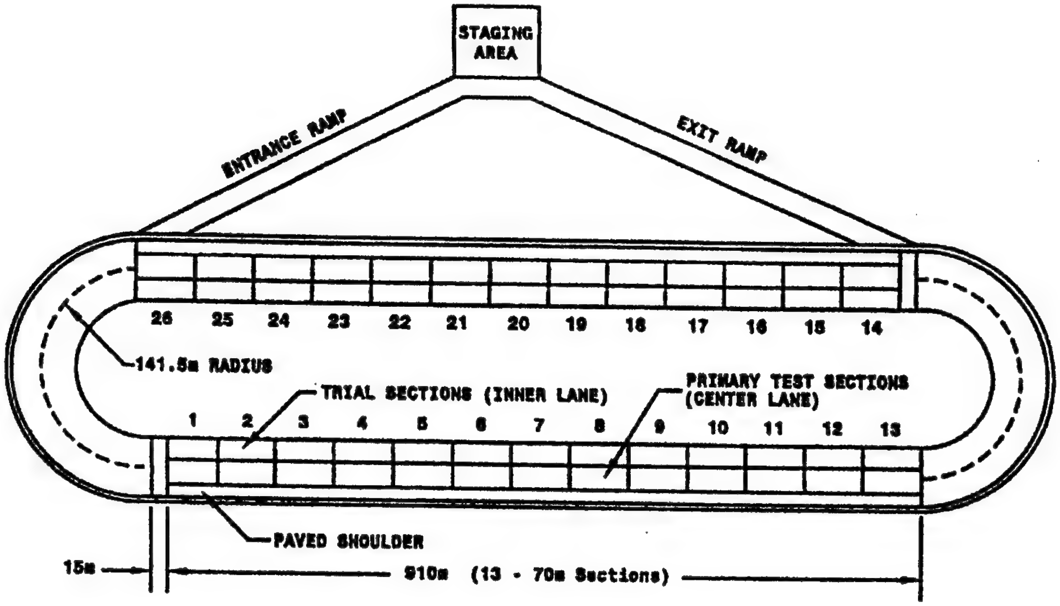


Figure 1-1: WesTrack Test Site Layout (not to scale)(3)

meters long by 10.4 meters wide consisting of two 3.6 meter paving lanes, a 1.8 meter gravel shoulder, and a 1.2 meter asphalt shoulder (See Figure 1-1). (3) All test sections are located along the tangent straightaway portions of the oval track. Each of the 26 sections was designed using the Superpave method with varied aggregate gradations, asphalt contents, and air void contents to represent common construction variability. (3) The WesTrack experiment was constructed and performed to achieve two primary objectives: 1) to continue the development of performance-related specifications for HMA pavements by evaluating the effect of deviations from optimum asphalt content, aggregate gradations, and in-place air void content; 2) to provide field verification for the new Superpave HMA mix design method. (3)

To rapidly simulate highway-loading conditions a system of 4 driverless tractor/ triple-trailer combinations were used on the track nearly 21 hours per day seven days per week. (3) Using this method of loading 2.8 million equivalent single axle loads (ESALs) were placed on the track by May 1997, resulting in severe rutting and fatigue cracking of 8 pavement sections. (3) After replacing these 8 sections, loading continued and as of June 1998, 4.8 million ESALs had been applied. (3) The performance of the track is monitored at varying intervals for different distress types; e.g., bi-monthly visual distress surveys, surface profile surveys, subsurface profile surveys, and longitudinal surveys; and monthly falling weight deflectometer (FWD) and surface friction measurements. (3)

The overall experiment design for the WesTrack program included 7 variable factors. These factors were asphalt binder type, asphalt binder content, aggregate type, aggregate gradation, aggregate shape and surface texture, in-place air void content, and

EXPERIMENT DESIGN FOR ORIGINAL 26 WESTRACK SECTIONS

Design Air Void Content	Aggregate Gradation Designation								
	Fine			Fine Plus			Coarse		
	Design Asphalt Contents (%)								
(%)	Low	Opt.	High	Low	Opt.	High	Low	Opt.	High
Low		04	18		12	09, 21		23 (39)	25 (55)
Medium	02	01/15	14	22	11/19	13	08 (38)	05/24 (35, 54)	07 (37)
High	03/16	17		10	20		26 (56)	06 (36)	

*Numbers shown in each cell represent WesTrack original construction section numbers, with replacement section numbers shown in parentheses.

Table 1-1: WesTrack Experiment Design (3)

section thickness. Due to financial constraints, only three of these variables were explored extensively, but it was believed that these three factors would capture the intent of the experiment adequately. (3) The three factors selected for the experiment were asphalt binder content, aggregate gradation, and in-place air void content (See Table 1-1). (3) The 4 factors that were removed from the experiment, binder type, aggregate type, aggregate shape and surface texture, and section thickness were held constant throughout the test.

1.3 TSRST Background

The thermal stress restrained specimen test (TSRST) is one of several tests developed since the mid 1960's which attempts to model the field conditions of asphalt concrete pavement under low temperatures. In the TSRST, a sample 50 mm x 50 mm x 250 mm, which is restrained to a constant length along its long axis, is exposed to a cooling rate of 10° C per hour while monitoring the developing thermal tensile stress. After extensive testing and evaluation of several different test methods, it was concluded that the TSRST has the greatest potential to evaluate the low-temperature cracking susceptibility of an asphalt concrete mixture. (4) The main advantages of the TSRST are as follows: the results may be used in mechanistic models; the test configuration simulates field conditions; the test is well documented, easy, and widely used. (4)

The TSRST system is made up of 4 main components including the load system, the data acquisition system, the temperature control system, and the specimen alignment stand. (4) The load system, which provides the resistance necessary to measure the tensile strength and eventually fracture the asphalt sample, is made up of a rigid frame, a

step motor, two swivel connectors, and two aluminum loading platens (See Figure 1-2). (4) The load frame, which is not exposed to test temperatures, simply acts as a mounting point for the step motor as it pulls on the asphalt concrete sample, keeping the sample at a constant length as it contracts under decreasing temperatures. Acting as an interface between the contracting AC sample and the step motor working to stop the sample contraction are two swivel connectors designed to eliminate eccentric loading and two aluminum loading platens. The aluminum loading platens facilitate the physical connection between the swivel connectors / step motor, using machined threads, and the AC sample using a two part mixed epoxy.

The data acquisition portion of the TSRST apparatus is made up of a transducer signal conditioner, a data acquisition/control unit, and a personal computer. (4) As a test specimen contracts due to decreasing temperature two linear variable differential transducers (LVDTs), attached at one end to a load platen and riding on invar rods attached to the second platen, detect this contraction. The LVDTs send their measurements first to the transducer signal conditioner and then to the data acquisition/control unit. (4) The data acquisition/control unit processes this information and signals to the step motor to pull the sample back to its original length. This cycle repeats as the sample temperature continues to drop, increasing the overall load, finally resulting in sample fracture. Monitoring the total specimen load, attached to the load frame and one load platen, is an electric load cell which relays data directly to the data collection unit. Attached directly to the test specimen are 4 thermistors, which read the sample surface temperature and relay these data directly to the data acquisition/control

unit. Every 30 seconds all the above data are taken and relayed to the personal computer, which records the data for later analysis.

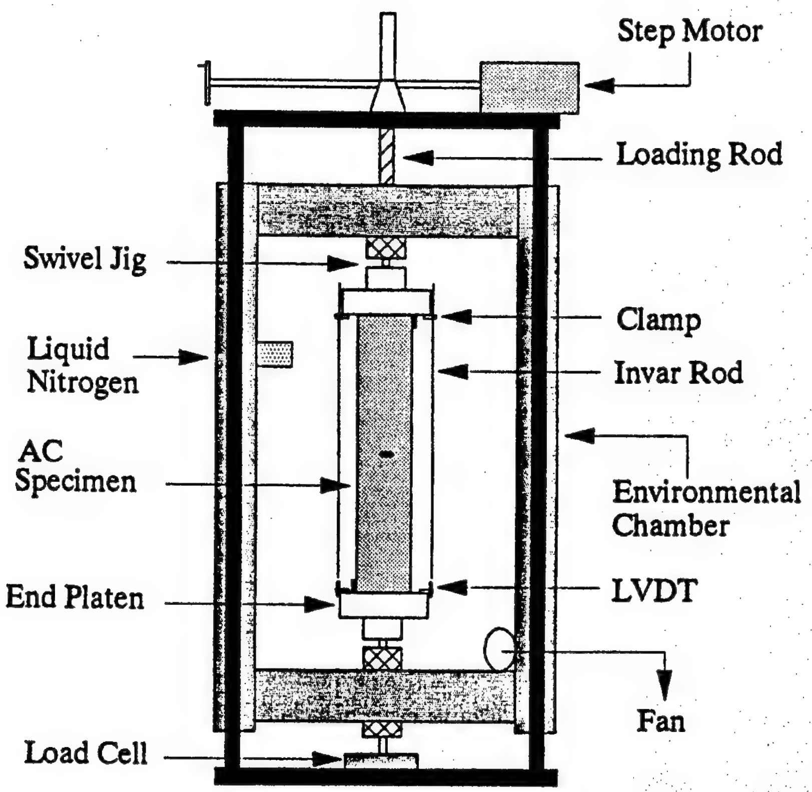


Figure 1-2: TSRST Apparatus Schematic (4)

The temperature control system operates separately from the data acquisition system and is made up of only 4 main components: they include the temperature controller, a liquid nitrogen supply container, an environmental chamber, and a resistance temperature device (RTD). (4) The RTD senses the temperature inside the environmental chamber, which houses the test sample, and relays this information to the temperature controller. (4) The temperature controller determines if the temperature inside the

chamber is correct according to the preprogrammed time-rate of cooling and adds vaporized liquid nitrogen as needed using a solenoid valve. (4)

Before a sample can be tested, it must be physically attached to two aluminum loading platens. This process is performed using epoxy as the bonding agent and a specimen alignment stand to ensure proper alignment with the load platens (See Figure 1-3). This is a very critical step in the test process since improper alignment can cause eccentric loading resulting in invalid test results. Samples placed in the alignment stand and epoxied to the load platens must be left undisturbed until the epoxy has had sufficient time to reach its full strength.

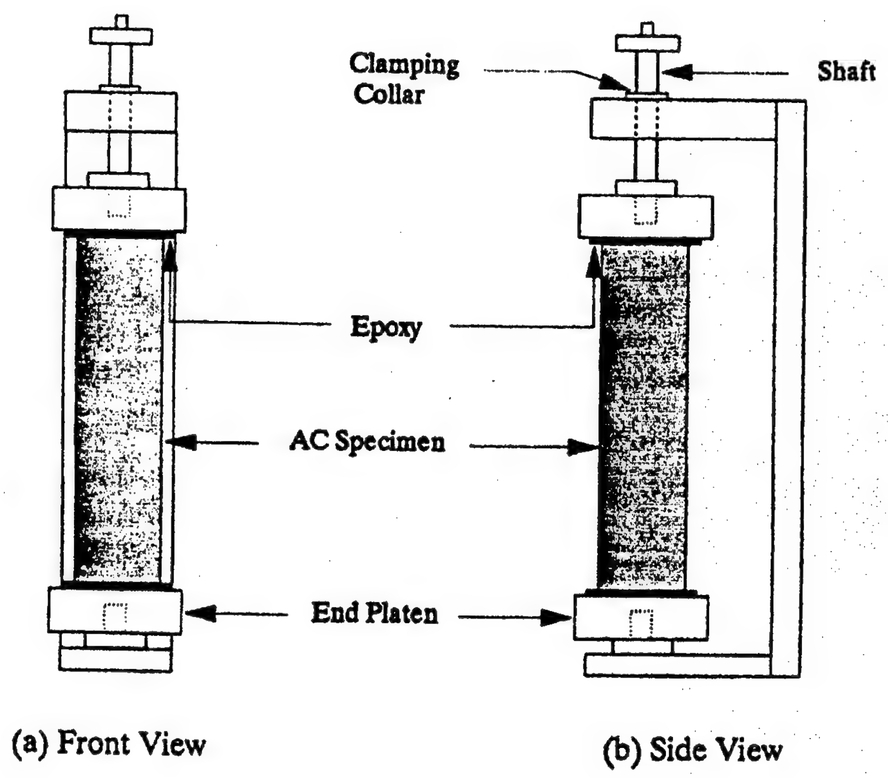


Figure 1-3: TSRST Sample Alignment Stand (4)

1.4 Experiment Hypothesis

The hypothesis for this experiment is that low temperature cracking, as measured by the TSRST, is not sensitive to aggregate gradation, binder content, air void content, or age conditioning.

1.4.1 Experiment Objectives

Three types of samples were evaluated to test the hypothesis: (FMFC) sawed from WesTrack test sections, (FMLC) plant mixed material for the WesTrack site compacted in the Oregon State University materials lab, and (LMLC) lab mixed WesTrack materials compacted in the Oregon State University materials lab. The TSRST data generated from these samples were used to assess the following: the relationship between FMFC, FMLC, and LMLC samples; the effects of asphalt content, air void content, aggregate gradation and age conditioning on the low temperature cracking behavior. Additionally an attempt was made to develop a multiple regression model for predicting fracture temperature of in-place asphalt concrete as a function of the previously noted variables for use in a performance related specification.

2.0 EXPERIMENT DESIGN

The overall experiment design for this study involved the fabrication and TSRST evaluation of nearly 120 specimens of dimensions 50 mm x 50 mm x 250 mm as shown in Table 2-2. The experiment was designed to quantify the effect of asphalt cement (AC) content, air void content, aggregate gradation, and aging on low temperature cracking behavior for use in a performance related specification.

The original experiment design called for the collection of data using a total of 14 different asphalt concrete mix designs and three sample sources (FMFC, FMLC, LMLC). Each mix would include an aggregate gradation (Fine, Coarse), an asphalt content (Low, Medium, High), and an air void content (Low, Medium, High). Triplicate samples would be created for each mix and for each method of mixing and compaction. Furthermore, duplicate sets of samples would be fabricated to assess the effect of aging: short-term vs. long-term. (See Table 2-1).

Coarse Aggregate Gradation - Short-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (5.0%)		LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)
Medium (5.7%)	LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)
High (6.4%)	LMLC (3) FMLC (3) FMFC (3)	LMLC (3) FMFC (3) FMLC (3)	

Coarse Aggregate Gradation - Long-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (5.0%)		LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)
Medium (5.7%)	LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)
High (6.4%)	LMLC (3) FMLC (3) FMFC (3)	LMLC (3) FMFC (3) FMLC (3)	

Fine Aggregate Gradation - Short-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (4.7%)		LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)
Medium (5.4%)	LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)
High (6.1%)	LMLC (3) FMLC (3) FMFC (3)	LMLC (3) FMFC (3) FMLC (3)	

Fine Aggregate Gradation - Long-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (4.7%)		LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)
Medium (5.4%)	LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)
High (6.1%)	LMLC (3) FMLC (3) FMFC (3)	LMLC (3) FMFC (3) FMLC (3)	

Notes: 1) Number next to identifier in # indicates quantity of samples to be tested for that particular mix.
2) Blacked out cells were not included in this experiment because of obvious difficulty in achieving these combinations. 3) Target AC contents were designated to be optimum (5.4% Fine, 5.7% Coarse) ± 0.7%.
4) Short-term aging consists of 4 hours @ 135° C (Loose Mix). Long-term aging consists of 120 hours @ 85° C.

Table 2-1: Original Experiment Design

Due to time and budgetary constraints, the scope of the project was reduced. All long-term aged samples were removed, as were nearly all of the fine aggregate gradation samples from both the FMFC and the FMLC portion of the study. The remaining samples, which were manufactured and tested in the TSRST, are as shown in Table 2-2.

<u>Coarse Aggregate Gradation - Short-Term Age</u>

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (5.0%)		FMFC (3) FMLC (3)	LMLC (3) FMFC (3) FMLC (3)
Medium (5.7%)	LMLC (3) FMFC (3) FMLC (3)	LMLC (3) FMFC (6) FMLC (6)	LMLC (3) FMFC (3) FMLC (3)
High (6.4%)	LMLC (3) FMLC (3) FMFC (3)	FMFC (3) FMLC (3)	

<u>Coarse Aggregate Gradation - Long-Term Age</u>

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (5.0%)			LMLC (3)
Medium (5.7%)	LMLC (3)	LMLC (3)	LMLC (3)
High (6.4%)	LMLC (3)		

<u>Fine Aggregate Gradation - Short-Term Age</u>

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (4.7%)			LMLC (3)
Medium (5.4%)	LMLC (3)	LMLC (3) FMLC (3) FMFC (6)	LMLC (3)
High (6.1%)	LMLC (3)		

<u>Fine Aggregate Gradation - Long-Term Age</u>

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (4.7%)			LMLC (3)
Medium (5.4%)	LMLC (3)	LMLC (2)	LMLC (3)
High (6.1%)	LMLC (3)		

Notes: 1) Number next to identifier in # indicates quantity of samples to be tested for that particular mix.
2) Blacked out cells were not included in this experiment because of obvious difficulty in achieving these combinations. 3) Target AC contents were designated to be optimum (5.4% Fine, 5.7% Coarse) ± 0.7%.
4) Short-term aging consists of 4 hours @ 135° C (Loose Mix). Long-term aging consists of 120 hours @ 85° C.

Table 2-2: Actual Experiment Design

2.1 Materials

2.1.1 Aggregate

A single aggregate quarried near Dayton, Nevada was selected as the primary aggregate source for use in construction of the original 26 sections. The aggregate was a partially crushed, fluvial deposit with a coarse natural gradation. (3) A total of 3 aggregate gradations were created with the Dayton aggregate for use in construction of the original 26 sections (fine, fine plus, and coarse). In creating the fine gradation, natural sand from Wadsworth, Nevada (approximately 25% by weight) was blended with the Dayton aggregate to meet the Superpave specifications on the fine side of the 19-mm nominal maximum size gradation curve. (3) The fine plus gradation was

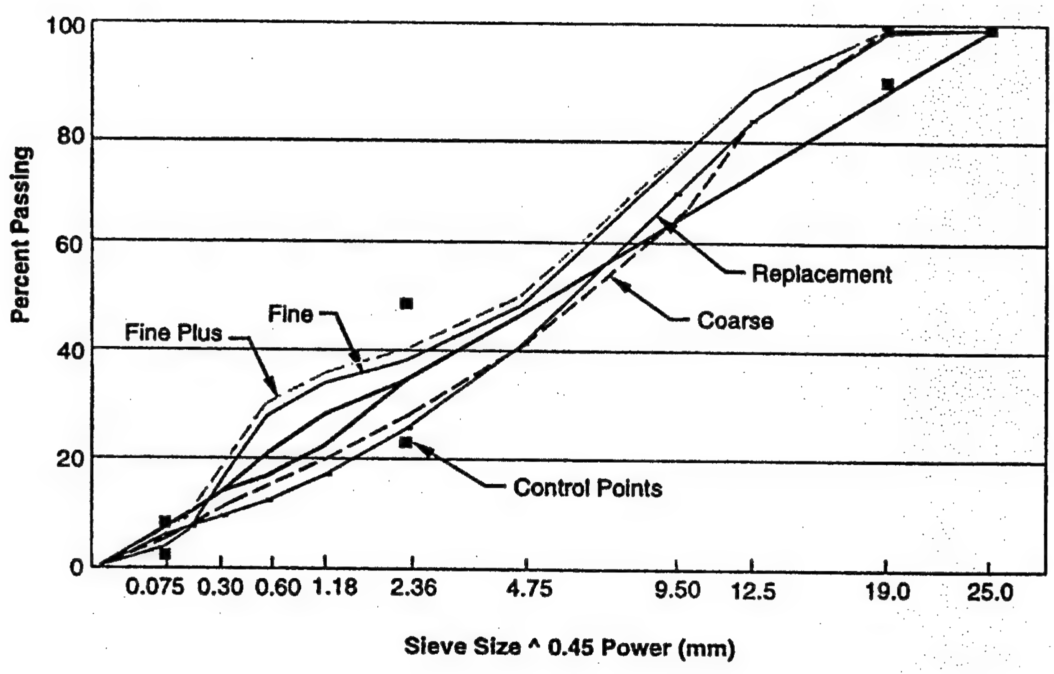


Figure 2-1: WesTrack Target Aggregate Gradations (3)

generated by simply adding 2% by weight of bag house fines to the original fine gradation. (3) The coarse gradation, which fell on the coarse side of the superpave 19-mm nominal max size curve, consisted of only the Dayton aggregate. See Figure 2-1 for WesTrack aggregate gradations and Table 2-3 for superpave aggregate specifications.

In June of 1997 eight sections of the WesTrack test facility were replaced due to pavement failure (Replacement section #'s 35-39, 54-56). (3) All of the failed sections were those constructed using the Dayton coarse aggregate gradation. To construct the replacement sections a gradation similar to the original coarse gradation was designed using 100% crushed andesite aggregate from the Lockwood quarry near Reno, Nevada (See Figure 2-1). (3)

Superpave Aggregate Specifications (WesTrack)					
Coarse Aggregate			Fine Aggregate		
Sieve Size SI (mm)	Sieve Size (in/#)	Spec % Passing	Sieve Size SI (mm)	Sieve Size (in/#)	Spec % Passing
19.00	3/4	100.0	19.00	3/4	100.0
12.50	1/2	79.2	12.50	1/2	88.1
9.50	3/8	65.0	9.50	3/8	76.6
4.75	#4	41.8	4.75	#4	51.1
2.36	#8	28.6	2.36	#8	39.8
1.18	#16	21.0	1.18	#16	35.2
0.60	#30	16.1	0.60	#30	28.7
0.30	#50	12.2	0.30	#50	16.1
0.15	#100	9.0	0.15	#100	8.1
0.08	#200	6.6	0.08	#200	5.0

Table 2-3: Mixture Target Gradations (3)

For the purposes of this experiment the fine plus gradation was deleted leaving only the fine and coarse gradations for testing as shown in Tables 2-1 and 2-2.

2.1.2 Asphalt Binder

A single performance graded asphalt binder PG 64-22 was selected for construction of the entire WesTrack test facility. This binder met the high temperature requirement at the 98-percentile level for the Superpave specification. (3) The low temperature grade was selected at the 50th percentile, as loading was not to exceed 3 years. (3) The PG 64-22 binder was used to fabricate all TSRST samples tested in this experiment.

2.1.3 Lime Additive

Mineral lime was added to all Westrack paving mixtures (1.5% by weight). The addition of lime to the paving mixtures was intended to prevent asphalt striping.

2.2 Sample Preparation

Once cut to the proper dimensions all TSRST samples were tested for air voids using either the saturated surface dry (SSD) or the parafilm techniques. The SSD method involves thorough drying the test specimen, determining the sample mass dry, submerged, and SSD. Sample air voids using the SSD method are calculated using equations 1 and 2.

$$G_{mb} = M_d / (M_{ssd} - M_{sub}) \quad (1)$$

$$\% \text{ Air Voids} = (1 - (G_{mb} / G_{mm})) \times (100) \quad (2)$$

G_{mb} = Sample Specific Gravity (Bulk)

G_{mm} = Asphalt Mix Maximum Theoretical Specific Gravity

M_d = Mass of sample dry

M_{ssd} = Mass of sample saturated surface dry

M_{sub} = Mass of sample submerged in water

To find air void contents using the parafilm method, samples were again thoroughly dried and the dry mass taken. Next, samples were wrapped in a thin layer of paraffin based film and the mass taken again to determine the mass of parafilm on the sample. To complete the process, the submerged mass of the sample was recorded. Sample air voids using the parafilm method are calculated using equations 3 and 2.

$$G_{mb} = M_d / (M_{w/para} - M_{sub} - ((M_{w/para} - M_d) / .9)) \quad (3)$$

$M_{w/para}$ = Dry Mass of sample wrapped in parafilm

The SSD method was used to calculate the bulk specific gravity of the low air void samples. This method was found to provide more consistent bulk specific gravity values on samples with small air voids (i.e. samples near 4% voids). To calculate the bulk specific gravity of the high air void samples (i.e. 12% voids), the parafilm method

was used. This method allowed large voids on the sample surface to be factored into the bulk specific gravity calculations thus avoiding erroneously high values. To calculate the bulk specific gravity of samples with mid range air voids (near 8% air voids), both the SSD and the parafilm methods were performed with the mean of these two values taken as the actual specific gravity.

2.2.1 FMFC

FMFC samples were taken from the as-constructed WesTrack sections. Larger than required pieces of each section were removed from the track surface and shipped to the Oregon State University materials testing laboratory. To create TSRST test specimens (50mm x 50mm x 250mm) these large sections were trimmed using a water-cooled concrete saw.

Individual asphalt mixes were batched off site using common component proportioning equipment and blended using a standard drum mixer. Once mixed, the HMA was trucked to the WesTrack facility and placed using common paving equipment with the assistance of a load transfer device (For more detail see WesTrack construction documentation, not included in this paper). In-place air content was established using standard compaction equipment and techniques. Due to the mass production conditions under which these samples were produced, the three variables under investigation have the potential to be more widely varied than samples mixed and or mixed and compacted in the lab.

2.2.2 FMLC

FMLC test samples were produced using asphalt concrete mixed during construction of the actual WesTrack test facility. Hence, FMLC samples were subject to the same mix proportioning variations (aggregate gradation and AC content) as FMFC samples. Material used for manufacture of FMLC samples was removed directly from haul-trucks and placed in sealed 5-gallon containers. This material was then shipped to the Oregon State University materials testing lab, where it was stored prior to compaction and testing.

Before the cooled field mixed asphalt concrete could be reheated and compacted to design densities, the proper compaction temperature for the PG 64-22 binder had to be determined. To accomplish this the binder was tested using the Brookfield viscosity tester. The binder was tested using the #21 spindle and at several different temperatures resulting in a recommended compaction temperature range of 133° C to 138° C (See Appendix A for details).

Field mixed HMA compacted in the OSU materials lab was reheated in its original steel 5-gallon shipping container using laboratory ovens. Once the HMA was warm enough to split, it was divided into 4.6 kg samples and placed in small laboratory pans to reach compaction temperatures.

The lab method of compaction selected for this study was the Hveem kneading compactor. The compaction process used for the FMLC portion of this study consisted of the following steps: First, a compaction mold (150mm x 150mm x 400mm) was heated to approximately 138° C and placed in the Hveem kneading compactor. Next, a single 4.6 kg pan of HMA, at compaction temperature, was placed in the mold and spread

evenly across the bottom. Using a predetermined compaction schedule for each separate mix/track section the Hveem compactor was activated applying a specified number of tamps at a specified pressure. The last two steps covered above were repeated three additional times for each compaction effort resulting in four lifts of compacted HMA in each compaction mold. Upon completing compaction of the fourth lift, the mold and compacted HMA were removed from the Hveem compactor and placed in a hydraulic press. A leveling load of 60,000 lbs. (27,200 kg) was applied to the HMA in the mold to remove compaction marks and square the resulting rectangular block. Finally, compacted HMA blocks and molds were allowed to cool over night before molds were removed.

Finished HMA blocks measured 150mm x 150mm x 400mm and weighed approximately 18.5 kg each. The size of these blocks produced four TSRST samples per block when sawed. The specific gravity and the percent air voids were calculated for each of the four samples and compared to target air voids for the track section being modeled. Samples with in plus or minus 1% of the target air voids were considered usable and included in the TSRST experiment, while samples falling outside that range were not.

2.2.3 LMLC

Raw materials from the WesTrack site were shipped directly to the Oregon State University materials testing lab to fabricate LMLC samples. These materials included mineral aggregates, PG 64-22 binder, and mineral lime. To obtain the proper aggregate gradations, (fine, coarse) all aggregates were sieved and separated according to

Superpave specified sieve sizes found in Table 2-3. Wet sieves were performed on the sieved aggregate for both the fine and coarse gradations, as shown in Table 2-3. After running several wet sieves for each gradation and adjusting batch proportions as required, the LMLC fine and coarse gradations found in Table 2-4 were established. Once proper mixing proportions of each aggregate size were determined batches of either fine or coarse aggregate weighing 5.4 kg each were prepared for future use. As stated earlier, 1.5% by weight of mineral lime was added to both the fine and the coarse gradations. This material was considered to consist of particles less than or equal to .08 mm in diameter. See Appendix B for lime addition procedures (6).

Superpave Aggregate Specifications and LMLC Mix Gradations (WesTrack)							
Coarse Aggregate				Fine Aggregate			
Sieve Size SI (mm)	Sieve Size (in/#)	Spec % Passing	LMLC As Blended	Sieve Size SI (mm)	Sieve Size (in/#)	Spec % Passing	LMLC As Blended
19.00	3/4	100.0	100.0	19.00	3/4	100.0	100.0
12.50	1/2	79.2	79.6	12.50	1/2	88.1	88.9
9.50	3/8	65.0	65.0	9.50	3/8	76.6	77.1
4.75	#4	41.8	44.5	4.75	#4	51.1	51.1
2.36	#8	28.6	28.5	2.36	#8	39.8	40.3
1.18	#16	21.0	20.7	1.18	#16	35.2	35.0
0.60	#30	16.1	16.1	0.60	#30	28.7	29.0
0.30	#50	12.2	12.1	0.30	#50	16.1	15.9
0.15	#100	9.0	8.8	0.15	#100	8.1	8.2
0.08	#200	6.6	6.6	0.08	#200	5.0	5.2

Table 2-4: LMLC Fine and Coarse Mix Gradations

Prior to mixing aggregate and asphalt cement (AC), the proper mixing and compaction temperatures for the PG 64-22 were determined. Using the Brookfield viscosity tester with the #21 spindle, several AC samples were tested at 4 different temperatures on the high and low sides of an assumed mixing and compaction temperature range. After plotting the resulting data on a viscosity (Pa-s) vs. temperature graph, the actual mixing temperature range was found to be between 144° C and 150° C. Using the same graph, the compaction temperature range was determined to be between 133° C and 138° C. See Appendix B for details.

Lab mixing of WesTrack HMA sections took place in four major steps, they include the following: material and equipment preparation; preheating and measuring of AC; physical mixing; and short term aging. Material and equipment preparation involved ensuring that all aggregate samples were thoroughly dried after being lime treated. Drying of lime treated aggregates was accomplished by placing each 5.4 kg pan of aggregate in a 110° C oven for a minimum of 18 hours. Equipment preparation included washing, drying and preheating steel mixing buckets, a mixing arm, and tools used to handle the HMA. The final step in preparing materials and equipment for mixing was to increase the temperature of both to between 144° C and 150° C (mixing temperature).

AC measuring and preheating was accomplished simultaneously with material and equipment preparation. One-quart cans of AC were used on a regular basis due to their ease of handling. AC was preheated using a natural gas burner and monitored with portable temperature probes. Upon reaching the predetermined mixing temperature (144° C - 150° C), the appropriate quantity of liquid AC was measured out for each 5.4 kg pan of dry aggregate.

Physical mixing of LMLC HMA took place in a portable rotating mixer. Only one pan (5.4 kg) of aggregate and the appropriate quantity of AC were mixed at any one time to ensure thorough and uniform mixing. Each batch of HMA was mixed for approximately 2 minutes before being removed and placed back into its original pan. The after mix temperature was taken for each batch of HMA to ensure that the minimum mixing temperature was maintained throughout the mixing process. For mixing details on individual LMLC, samples see Appendix B.

The final step in the lab mixing process was to short-term age all HMA produced. Lab short-term aging was intended to simulate the 3-4 hours of elevated temperatures after plant mixing that all HMAs are subject to in the field. The lab procedure for short-term aging consisted of placing freshly mixed HMA in a 135° C oven for 4 hours. Every hour, samples were removed from heat and hand mixed to prevent bleeding of AC. Immediately following completion of short-term aging at 135° C, the temperature of the lab mixed HMA was increased to approximately 138° C in preparation for lab compaction.

Again, the lab method of compaction selected for this study was the Hveem kneading using the Hveem kneading compactor. The compaction process used for the LMLC portion of this study consisted of the following steps: first, a compaction mold (150mm x 150mm x 400mm) was heated to approximately 138° C and placed in the Hveem kneading compactor. Next, a single 5.4 kg pan of HMA, at compaction temperature, was placed in the mold and spread evenly across the bottom. Using a predetermined compaction schedule for each separate mix/track section the Hveem compactor was activated, applying a specified number of tamps at a specified pressure.

The last two steps covered above were repeated one additional time for each compaction effort resulting in two lifts of compacted HMA in each compaction mold. Upon completing compaction of the second lift, the mold and compacted HMA were removed from the Hveem compactor and placed in a hydraulic press. A leveling load of either 40,000 or 60,000 lbs. (27,200 or 18,100 kg) was applied to the HMA in the mold to remove compaction marks and square the resulting rectangular block. Finally, compacted HMA blocks and molds were allowed to cool over night before molds were removed. See Appendix B for sample compaction schedules.

Finished HMA blocks measured 90mm x 150mm x 400mm and weighed approximately 11 kg each. The size of these blocks, unlike the FMLC sections, produced only two TSRST samples per block when sawed. The specific gravity and the percent air voids were calculated for both samples and compared to target air voids for the track section being modeled. Samples with in $\pm$ 1% of the target air voids were considered usable and included in the TSRST experiment, while samples falling outside that range were not. See Appendix B for volumetric sample results and theoretical maximum specific gravities.

The LMLC portion of this study, unlike the FMFC or the FMLC portions included long-term aging as a variable in production of TSRST samples. For each WesTrack section modeled in the LMLC portion of this study a total of six test samples were produced. Three samples received only short-term aging just as samples in the FMFC and FMLC categories. The three additional samples received both short-term and long-term aging.

The long-term aging process for TSRST samples consisted of placing samples flat on a bed of fine-grained sand to support any surface irregularities. Samples were then placed in a sealed oven for 120 hours at a temperature of 85° C. The lab long-term aging process is intended to model the oxidation and exposure that a pavement in the field would experience. Upon completion of long-term aging, samples were allowed to cool, removed from the sand bed and placed in refrigerated coolers with their short-term aged counterparts to await the TSRST.

2.3 TSRST Testing

Thermal stress restrained specimen testing for all samples (FMFC, FMLC, and LMLC) was performed in the Oregon State University materials testing lab. The entire TSRST process used can be broken down into two major steps; these include the sample preparation and the sample testing and data recording. Sample preparation for the TSRST includes three primary steps. First, aluminum loading platens were fastened to either end of the test specimens using a two-part epoxy. Using the sample alignment stand described in section 1.3, the loading platens were attached as nearly perpendicular as possible to the long axis of each sample to avoid excessive eccentric loading (See Figure 2-2). The epoxy used for this experiment required a minimum of 12 hours cure time before testing could resume. Next, samples successfully mounted on TSRST loading platens were placed in the TSRST cabinet and attached to the step motor mounting points. Also attached at this time were all data collection instruments. Finally, after all testing equipment was attached and calibrated, the cabinet door was sealed and

the sample cooled at a rate of 30° C per hour to an equilibrium temperature of 2° C. At this temperature, the sample testing was initiated.

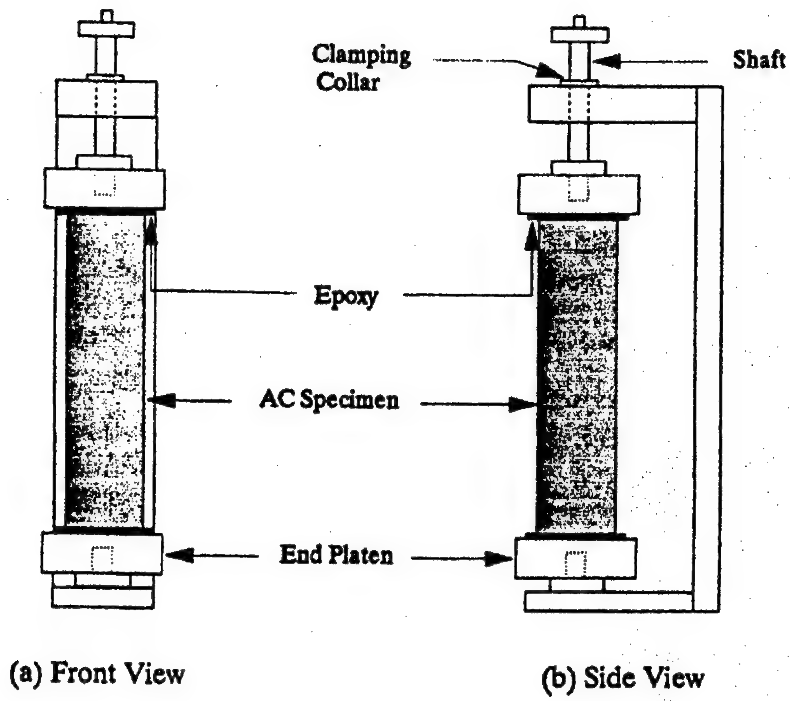


Figure 2-2: Sample Alignment Stand (4)

Sample testing was performed using a cooling rate of 10° C per hour. Recorded every 30 seconds were four temperature readings from different locations on the surface of the test specimen, sample deflection, and sample loading. Testing was continued until the fracture strength of the specimen was surpassed. See Appendix C for more detailed TSRST procedures (7).

After testing, the average cross sectional area of each sample was found by measuring at three points along the fractured test sample. The overall sample fracture strength was then calculated using the maximum attained sample load during testing and the average sample cross sectional area. See Appendix C for sample dimensions.

3.0 TEST RESULTS, ANALYSIS AND DISCUSSION

3.1 FMFC

Thirty FMFC short-term aged TSRST samples were tested in this experiment. Twenty-four of these samples were fabricated using the coarse aggregate gradation and six using the fine aggregate gradation, as shown in Table 3-1. With only six samples containing the fine aggregate gradation, the conclusions drawn from these tests are extremely weak with respect to the aggregate gradation variable. In spite of this, the six fine aggregate samples were included in the study since they did provide some information on the effects of aggregate gradation.

Coarse Aggregate Gradation - Short-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (5.0%)		FMFC (3)	FMFC (3)
Medium (5.7%)	FMFC (3)	FMFC (6)	FMFC (3)
High (6.4%)	FMFC (3)	FMFC (3)	

Fine Aggregate Gradation - Short-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (4.7%)			
Medium (5.4%)		FMFC (6)	
High (6.1%)			

Notes: 1) Number next to identifier in # indicates quantity of samples to be tested for that particular mix.
2) Blacked out cells were not included in this experiment because of obvious difficulty in achieving these combinations.

Table 3-1: FMFC Test Data

No long-term aged FMFC TSRST samples were included in this experiment, therefore the variable age conditioning, is left out of the FMFC portion of the data analysis.

3.1.1 Air Void Content

As expected, the calculated air void contents of the FMFC samples were considerably different than the targets specified by the experiment. Low air void (4.0%

target) sections 25 and 39 had average air voids of 2.6% and 3.9%, respectively. High air void (12.0% target) sections 26 and 36 had average air voids of 8.4% and 12.4%, respectively. Samples with target air voids of 8.0%, sections 01, 24, 35, 37, and 38 contained air voids of 9.1%, 4.5%, 8.0%, 9.1%, and 7.2% respectively, (See Figure 3-8). While these values were not right on target, they were reasonable considering the inherent variability associated with field construction. See Figure 3-1 for FMFC average section air void contents.

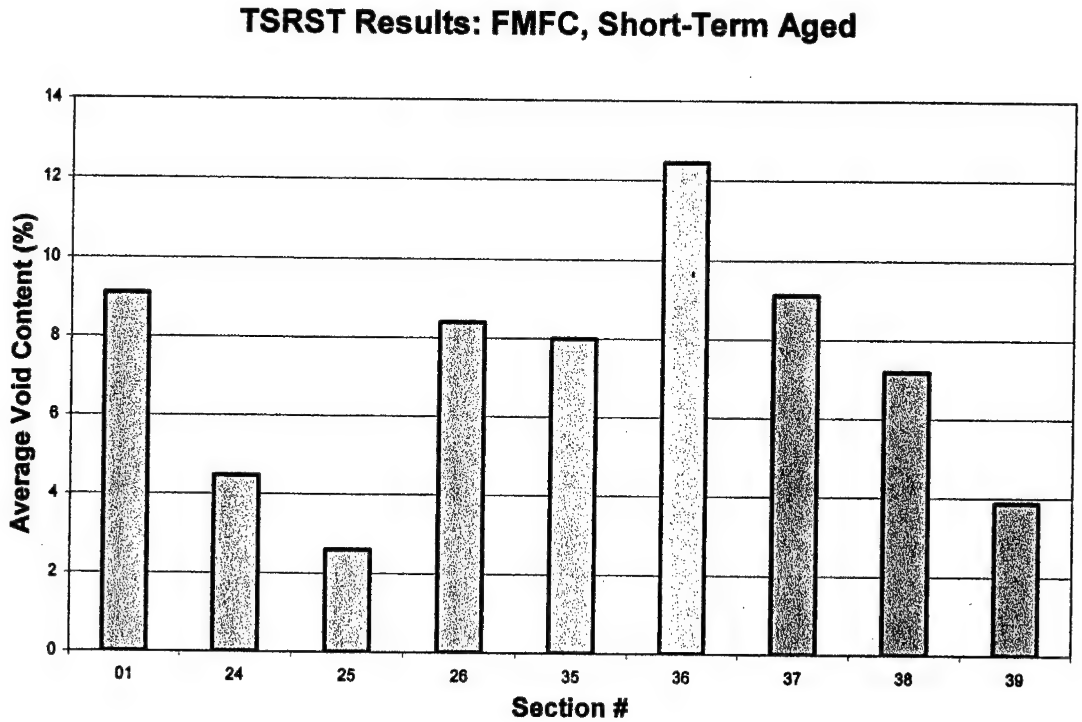


Figure 3-1: Average Section Air Void Contents (FMFC)

3.1.2 Fracture Temperatures

Fracture temperature is defined as the temperature at which the thermal stress induced in the specimen is maximum (See Figure 3-2). (5) A summary of average

fracture temperatures for the FMFC portion of this experiment can be found in Table 3-2. A graphical representation of the same data is shown in Figure 3-3.

Sample fracture temperatures for the FMFC portion of this study ranged from -16.1° C to -35.0° C with section 01 having the highest overall average fracture temperature of -18.5° C. Samples fabricated with the fine aggregate gradation had a fracture temperature range of -16.1° C to -22.5° C with an average of -18.5° C, while samples fabricated with the coarse aggregate gradation had a range of -19.2° C to -35.0° C with an average of -24.4° C. The average difference in fracture temperature between the two gradations was 5.9° C.

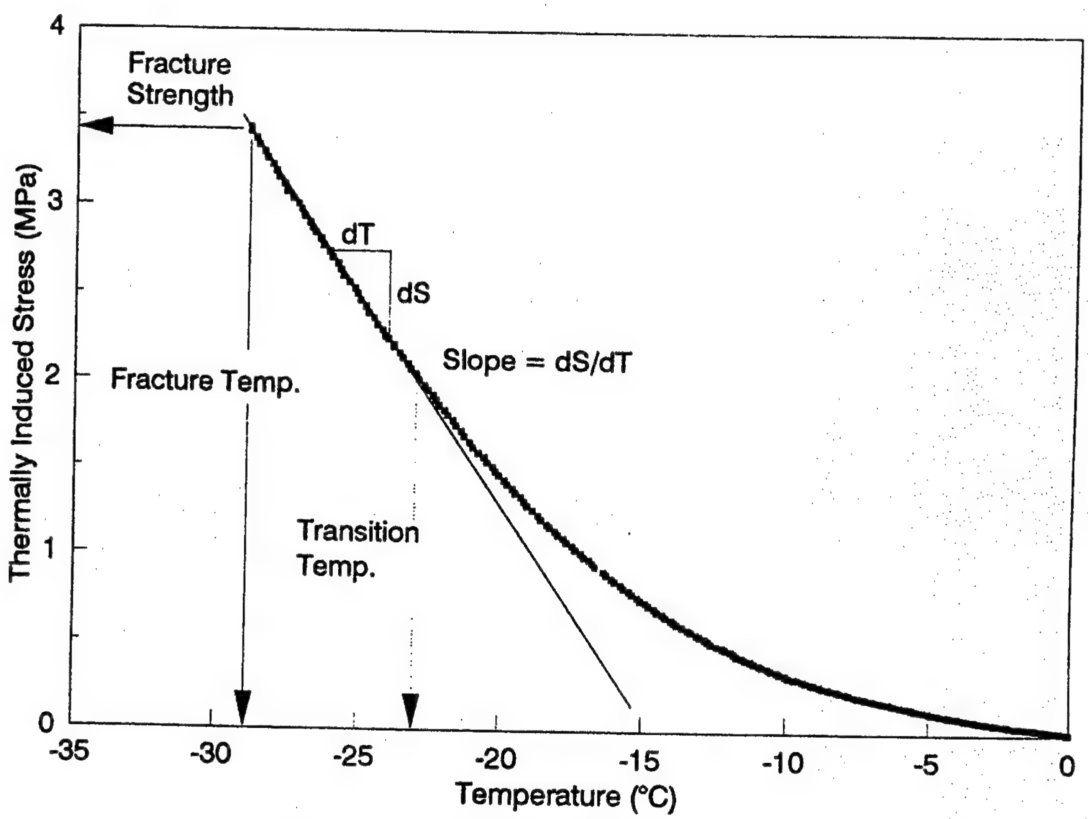


Figure 3-2: Typical Stress vs. Temperature Curve (5)

WesTrack Project: Summary of TSRST Data Field Mix Field Compacted, Short-Term Aged					
Section / AC Content	Average Void Content	Average Tensile Strength		Average Fracture Temperature	
	(%)	(MPa)	(psi)	^0C	^0F
01 M	9.1	1.81	262	-18.5	-1.2
24 M	4.5	2.98	432	-23.2	-9.8
25 H	2.6	2.88	417	-21.3	-6.3
26 L	8.4	2.35	341	-20.8	-5.5
35 M	8.0	1.95	283	-25.8	-14.5
36 M	12.4	1.16	168	-28.7	-19.7
37 H	9.1	1.80	262	-24.3	-11.8
38 L	7.2	2.54	369	-26.8	-16.2
39 M	3.9	2.98	433	-24.6	-12.2

Table 3-2: FMFC Data Summary

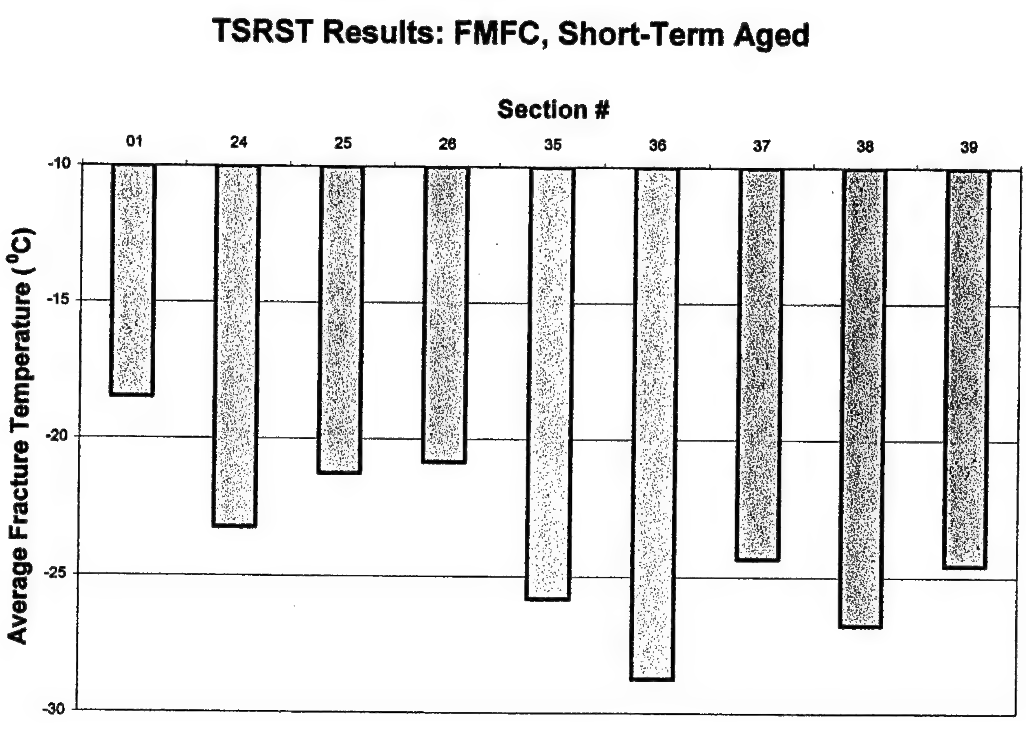


Figure 3-3: Average Section Fracture Temperatures (FMFC)

Samples fabricated with low, medium, and high AC contents had fracture temperature ranges of -20.3° C to -27.4° C, -16.1° C to -35.0° C, and -19.2° C to -25.1° C, respectively. The average fracture temperatures for the low, medium, and high AC content samples were -23.8° C, -23.2° C, and -22.8° C, respectively. The difference in fracture temperature between specimens with high and low asphalt content was 1.0°C.

Samples fabricated with low, medium, and high air void contents had fracture temperature ranges of -19.2° C to -25.4° C, -16.1° C to -27.4° C, and -20.3° C to -35.0° C, respectively. The average fracture temperatures for the low, medium, and high air void content samples were -23.0° C, -22.7° C, and -24.8° C respectively. The difference in fracture temperature between specimens with high and the low air void contents was 2.1° C. See Table 3-3 for a summary of average results versus mixing and compaction variables.

FMFC TSRST Average Fracture Temperature Results					
Mix or Comaction Variable / Sample Averages					
Air Void Content	Sample Averages (°C)	AC Content	Sample Averages (°C)	Agg Gradation	Sample Averages (°C)
Low	-23.0	Low	-23.8	Fine	-18.5
Medium	-22.7	Medium	-23.2	Coarse	-24.4
High	-24.8	High	-22.8		
Minimum	-22.7	Minimum	-22.8	Minimum	-18.5
Maximum	-24.8	Maximum	-23.8	Maximum	-24.4
Difference	**2.1**	**Difference**	**1.0**	**Difference**	**5.9**

Table 3-3: FMFC Average Fracture Temperature Results Versus Mixing and Compaction Variables

3.1.3 Fracture Strengths and Loading Rates

Fracture strength is defined as the maximum stress developed at fracture. (5) The fracture strength data developed from the FMFC TSRST portion of this experiment are

summarized in Table 3-2 and in Figure 3-4. The WesTrack section demonstrating the lowest average fracture strength was section 36 with an average of only 1.16 MPa. The sections with the highest average fracture strength, both 2.98 MPa, were sections 24 and 39.

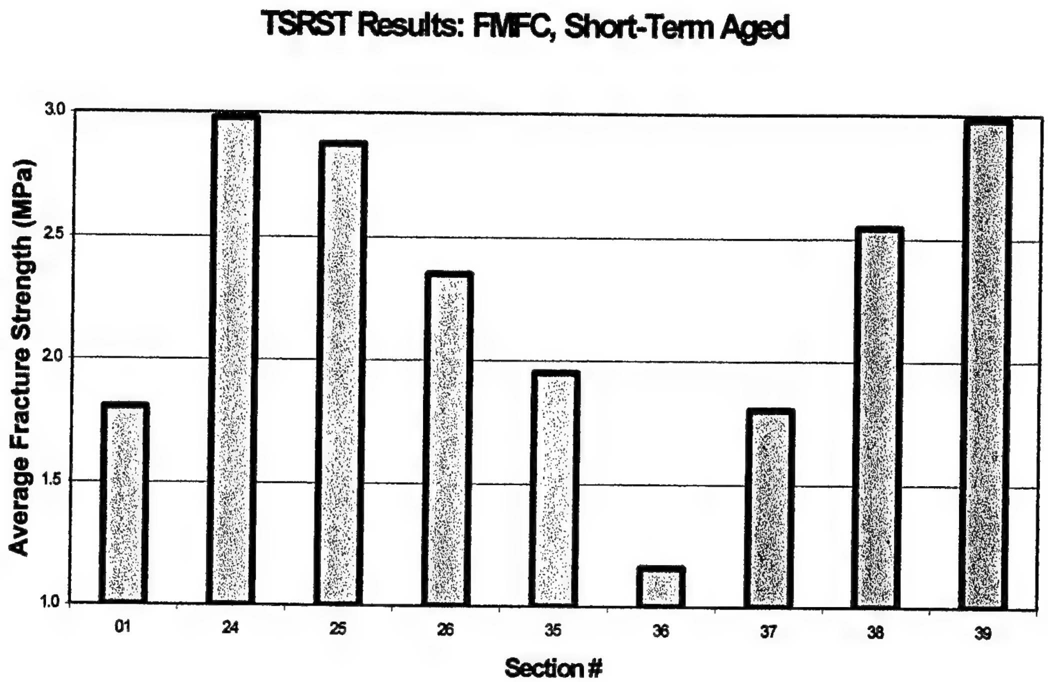


Figure 3-4: Average Section Fracture Strengths (FMFC)

Sample loading rates, or the slope of the stress versus temperature curves for individual FMFC TSRST samples along with sample fracture strengths and temperatures, are found in Appendix D. Average stress versus temperature curves depicting relationships between air void content, AC content, and aggregate gradation for each FMFC WesTrack section are shown in Figures 3-5, 3-6, and 3-7. In these figures,

average WesTrack section curves are sorted by air void content, AC content and aggregate gradation to show their effect on loading rate.

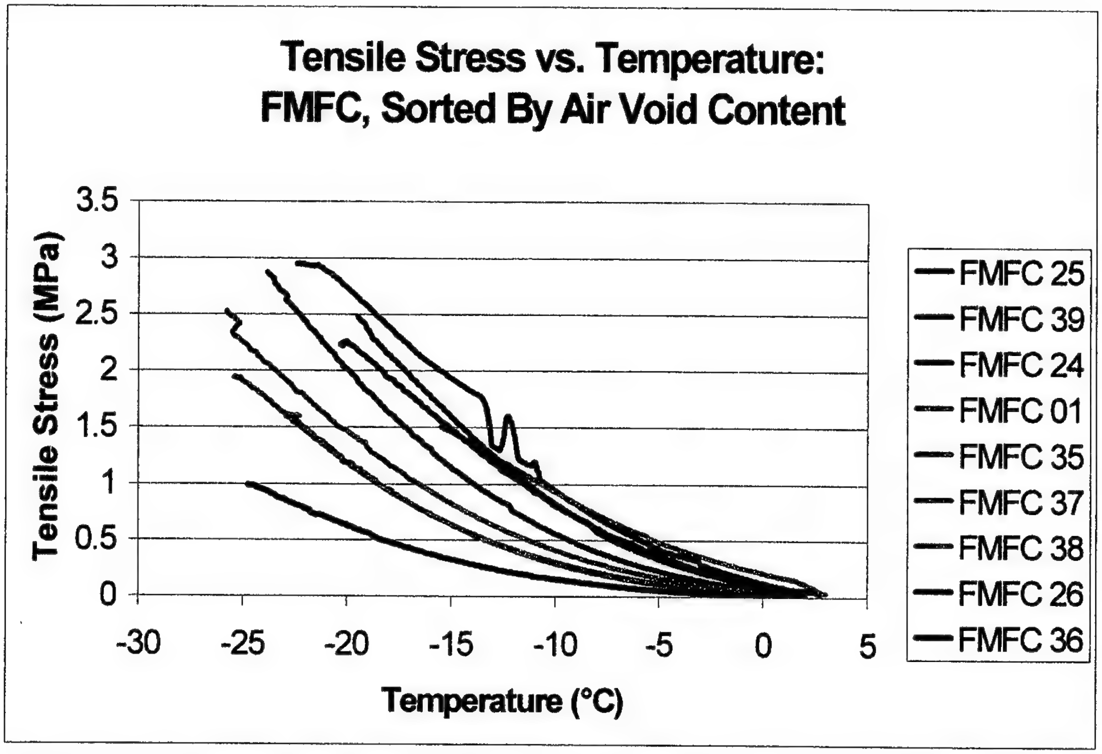


Figure 3-5: Average Section TSRST Curves Sorted by Air Void Content (FMFC)
(Red = 4% Air Voids, Blue = 8% Air Voids, Black = 12% Air Voids)

Figure 3-5 indicates that air void content plays a role in determining the loading rate of WesTrack asphalt concrete. The low air void content sample curves highlighted in red appear to be above average in their loading rate, gaining load quicker and at lower temperatures than either medium or high air void samples. The medium air void sample curves highlighted in blue appear to be evenly distributed in the middle of the graph, while the high air void sample curve falls on the lower half of the plot indicating a slower loading rate. Based on Figures 3-5, 3-6, and 3-7, no single variable appears to dominate loading rate.

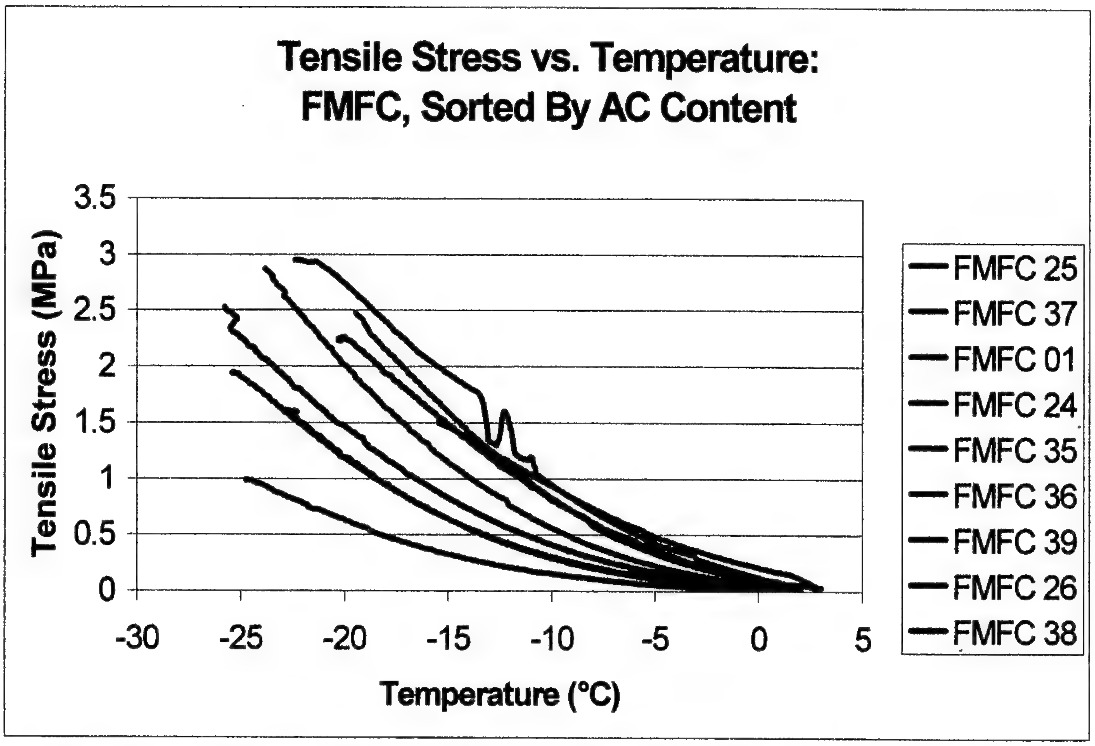


Figure 3-6: Average Section TSRST Curves Sorted by AC Content (FMFC)
(Red = High AC Content, Blue = Medium AC Content, Black = Low AC Content)

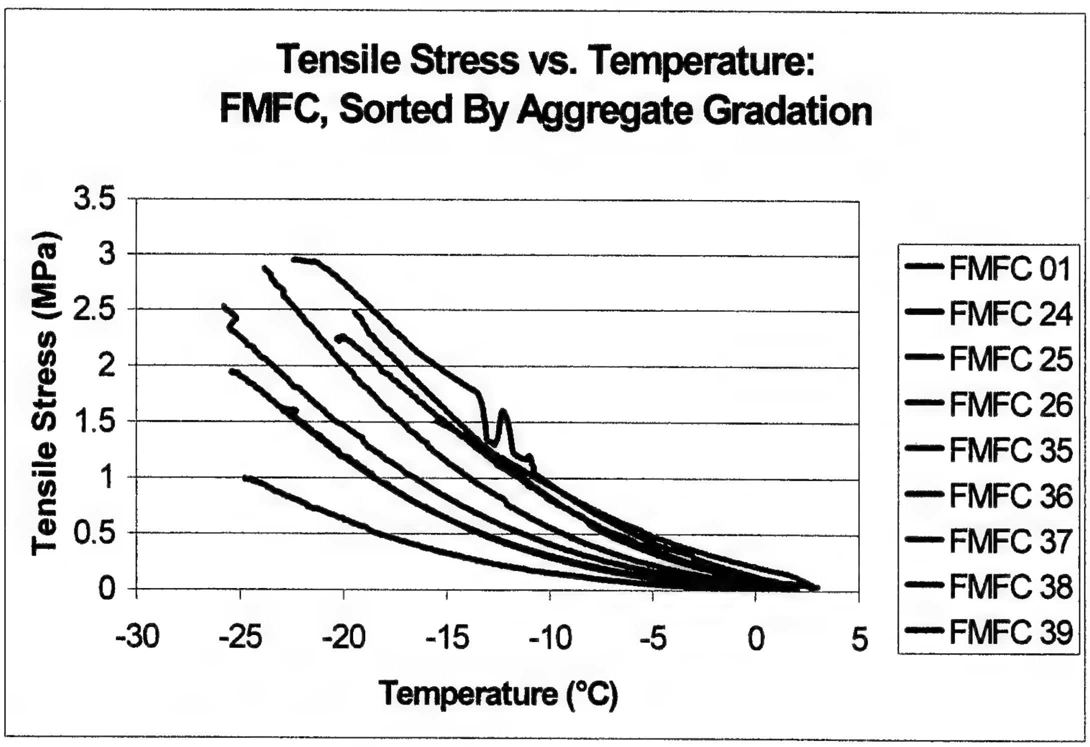


Figure 3-7: Average Section TSRST Curves Sorted by Aggregate Gradation (FMFC)
(Red = Fine Aggregate Gradation, Black = Coarse Aggregate Gradation)

3.1.4 Statistical Analysis and Discussion

The primary experimental indicator of an asphalt concrete mixtures susceptibility to low temperature cracking is the sample fracture temperature. For this reason, only the fracture temperature data generated from this study will be statistically analyzed.

Due to the relative small sample sizes involved with each method of sample mixing and compaction (FMFC, FMLC, LMLC), the primary focus of the statistical analysis will be on the combined data set found at the end of this chapter.

To analyze the FMFC fracture temperature data, a correlation matrix was constructed showing the strength of relationships between input variables and fracture temperature (See Table 3-4).

FMFC Correlation Coefficient Matrix					
	Fracture Temp	% Air Voids	Age Cond	% AC Cont	Agg Grad
Fracture Temp	1.00				
% Air Voids	-0.14	1.00			
Age Cond					
% AC Cont	-0.09	-0.27		1.00	
Agg Grad	-0.62	-0.28		0.06	1.00

Table 3-4: FMFC Correlation Matrix

The relatively strong (-.62) correlation between aggregate gradation and fracture temperature parallels the large difference in average fracture temperature between fine and coarse aggregate mixes found in section 3.1.2. The correlation coefficients calculated for % AC content (-.09) and % air voids (-.14) versus fracture temperature are insignificant, similar to the differences in average values found in section 3.1.2.

Looking only at the FMFC fracture temperature data, aggregate gradation is the single most important variable contributing to low temperature cracking susceptibility of WesTrack pavements. Samples fabricated with the fine aggregate gradation failed on average 5.9° C warmer than samples fabricated with the coarse aggregate gradation. Air void content and AC content appear to have some, but very little effect on fracture temperature. Due to the small number of samples tested, these results should be viewed cautiously.

3.2 FMLC

Twenty-seven FMLC short-term aged TSRST samples were tested in this experiment. Twenty-four of these samples were fabricated using the coarse aggregate gradation and three using the fine aggregate gradation (See Table 3-5). With only three samples containing the fine aggregate gradation, the conclusions drawn from these tests are extremely weak with respect to the aggregate gradation variable. In spite of this, the three fine aggregate samples were included in the study since they did provide some information on the effects of aggregate gradation.

Coarse Aggregate Gradation - Short-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (5.0%)		FMLC (3)	FMLC (3)
Medium (5.7%)	FMLC (3)	FMLC (6)	FMLC (3)
High (6.4%)	FMLC (3)	FMLC (3)	

Fine Aggregate Gradation - Short-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (4.7%)			
Medium (5.4%)		FMLC (3)	
High (6.1%)			

Notes: 1) Number next to identifier in # indicates quantity of samples to be tested for that particular mix.
2) Blacked out cells were not included in this experiment because of obvious difficulty in achieving these combinations.

Table 3-5: FMLC Test Data

No long-term aged FMLC samples were included in this experiment, therefore the variable age conditioning is left out of the FMLC portion of the data analysis.

3.2.1 Air Void Content

The air void content of samples mixed in the field and compacted in the OSU materials laboratory varied significantly from experiment designated target air voids. This was particularly surprising given the capability to tightly control compaction, and thus air void content in a laboratory environment. Low air void (4.0% target) sections 25 and 39 had average air voids of 3.0% and 8.1%, respectively. High air void (12.0% target) section 26 and 36 had average air voids of 6.9% and 7.6%, respectively. Samples with target air voids of 8.0%, sections 01, 24, 35, 37, and 38 had average air voids of 9.0%, 4.9%, 7.8%, 7.6%, and 8.1%, respectively, as shown in Figure 3-8.

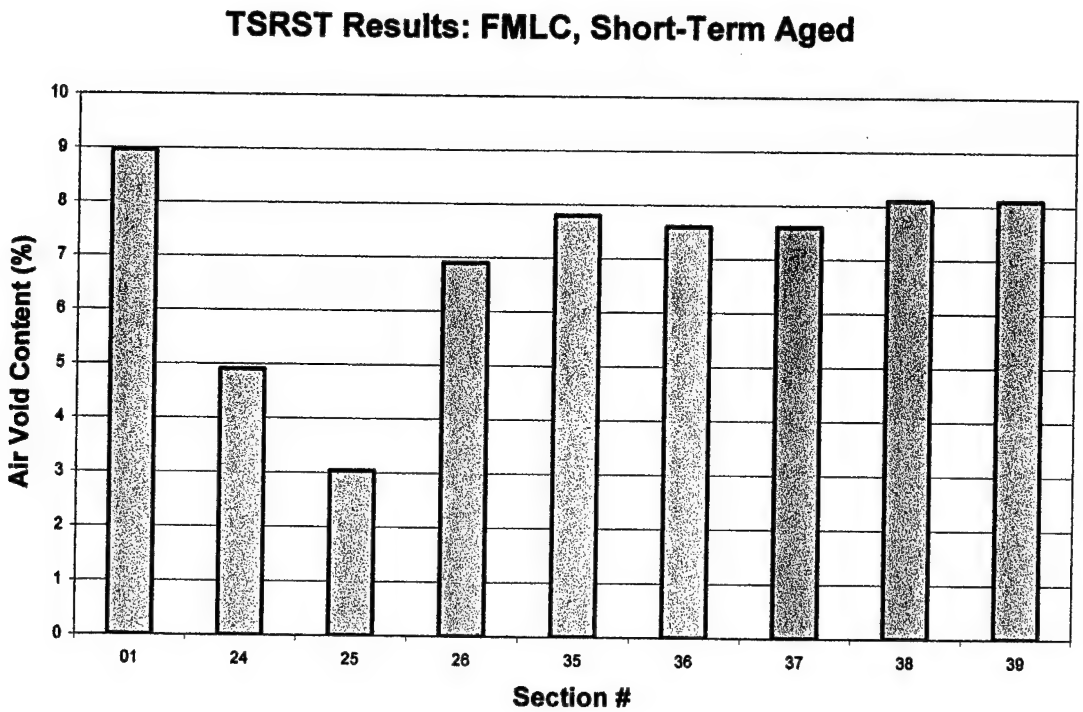


Figure 3-8: Average Section Air Void Contents (FMLC)

3.2.2 Fracture Temperatures

See Table 3-6 for a summary of average FMLC section fracture temperatures. A graphical representation of the same data is shown in Figure 3-9.

Sample fracture temperatures for the FMLC portion of this study ranged from -13.3° C to -28.8° C with section 26 having the highest overall average fracture temperature of -18.2° C. Samples fabricated with the fine aggregate gradation had a fracture temperature range of -19.6° C to -28.8° C with an average of -24.0° C, while samples fabricated with the coarse aggregate gradation had a range of -13.3° C to -25.9° C with an average of -21.5° C. The average difference in fracture temperature between the two gradations was 2.5° C.

Samples fabricated with low, medium, and high AC contents had fracture temperature ranges of -13.3° C to -23.1° C, -18.2° C to -28.8° C, and -21.0° C to -25.9° C, respectively. The average fracture temperatures for the low, medium, and high AC content samples were -19.8° C, -22.0° C, and -23.1° C, respectively. The difference in fracture temperature between specimens with high and low asphalt content was 3.3° C.

Samples fabricated with low, medium, and high air void contents had fracture temperature ranges of -21.0° C to -25.9° C, -18.2° C to -28.8° C, and -13.3° C to -23.1° C, respectively. The average fracture temperatures for the low, medium, and high air void content samples were -22.4° C, -22.3° C, and -19.8° C, respectively. The difference in fracture temperature between specimens with high and the low air void contents was 2.6° C. See Table 3-7 for a summary of average results versus mix parameters and compaction variables.

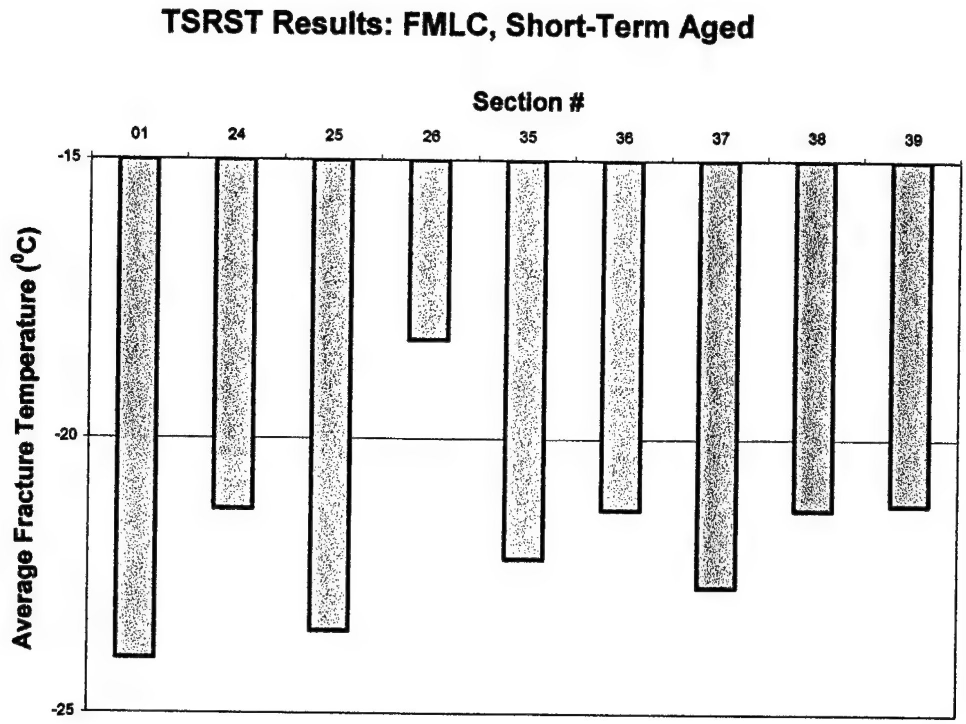


Figure 3-9: Average Section Fracture Temperatures (FMLC)

WesTrack Project: Summary of TSRST Data Field Mix Lab Compacted, Short-Term Aged					
Section / AC Content	Average Void Content	Average Tensile Strength		Average Fracture Temperature	
	(%)	(MPa)	(psi)	°C	°F
01 M	9.0	1.47	213	-24.0	-11.2
24 M	4.9	2.21	320	-21.3	-6.3
25 H	3.0	2.54	369	-23.5	-10.3
26 L	6.9	0.61	88	-18.2	-0.8
35 M	7.8	2.14	311	-22.2	-7.9
36 M	7.6	2.20	319	-21.3	-6.3
37 H	7.6	2.07	300	-22.7	-8.9
38 L	8.1	2.72	394	-21.3	-6.3
39 M	8.1	1.66	240	-21.2	-6.2

Table 3-6: FMLC Data Summary

FMLC TSRST Average Fracture Temperature Results					
Mix or Comaction Variable / Sample Averages					
Air Void Content	Sample Averages (°C)	AC Content	Sample Averages (°C)	Agg Gradation	Sample Averages (°C)
Low	-22.4	Low	-19.8	Fine	-24.0
Medium	-22.3	Medium	-22.0	Coarse	-21.5
High	-19.8	High	-23.1		
Minimum	-19.8	Minimum	-19.8	Minimum	-21.5
Maximum	-22.4	Maximum	-23.1	Maximum	-24.0
Difference	**2.6**	**Difference**	**3.3**	**Difference**	**2.5**

Table 3-7: FMLC Average Fracture Temperature Results Versus Mixing and Compaction Variables

3.2.3 Fracture Strengths and Loading Rates

The fracture strength data developed from the FMLC TSRST portion of this experiment are summarized in Table 3-6 and Figure 3-10. The WesTrack section demonstrating the lowest average fracture strength was section 26 with an average of only .61 MPa. The section with the highest average fracture strength (2.72 MPa) was section 38.

Sample loading rates, or the slope of the stress versus temperature curves for individual FMLC TSRST samples along with sample fracture strengths and temperatures are found in Appendix E. Average stress versus temperature curves depicting relationships between air void content, AC content, and aggregate gradation for each FMLC WesTrack section are located in Figures 3-11, 3-12, and 3-13. In these figures, average WesTrack section curves are sorted according to air void content, asphalt content, and aggregate gradation to show their effect on loading rate.

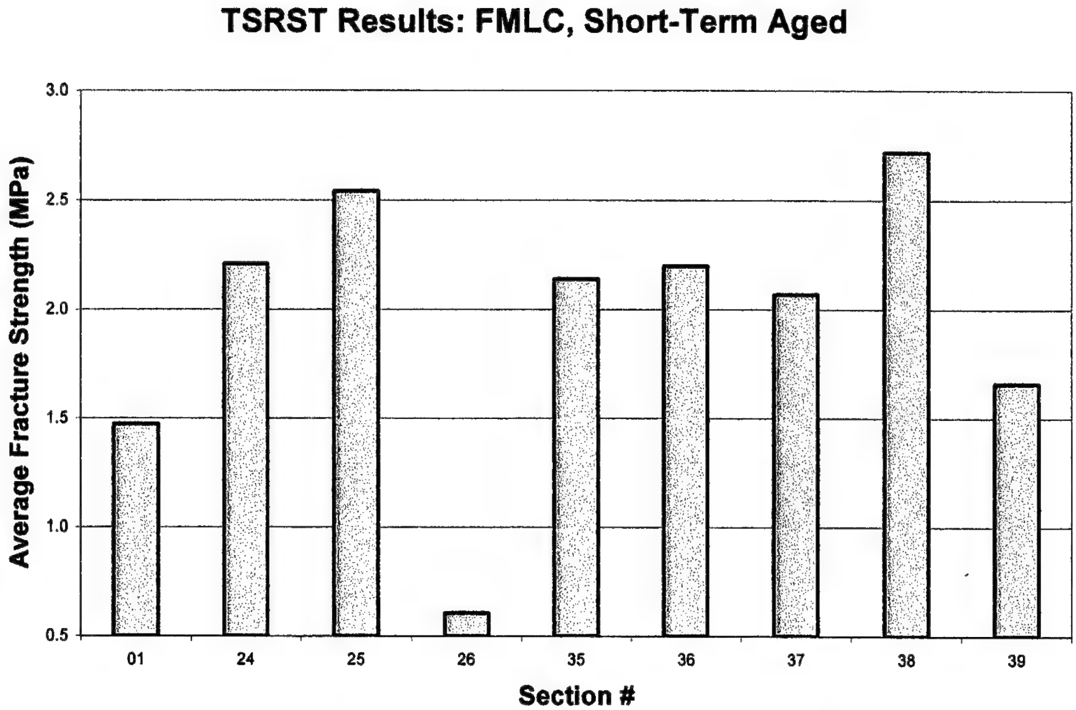


Figure 3-10: Average Section Fracture Strengths (FMLC)

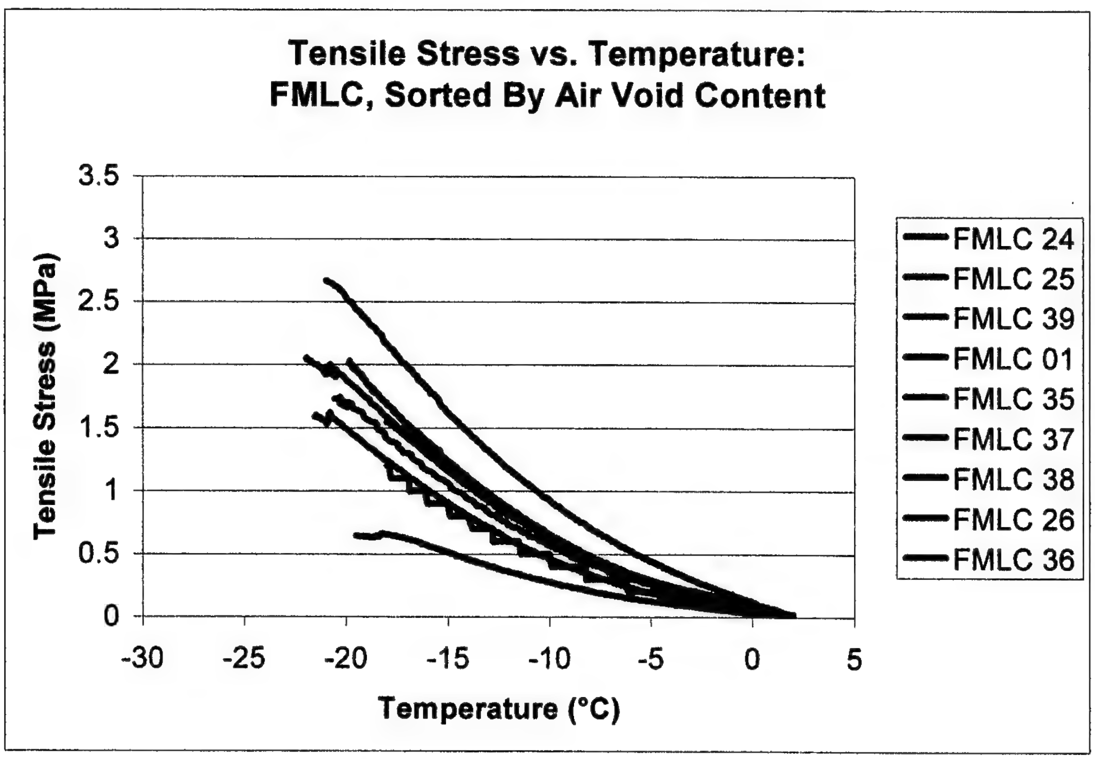


Figure 3-11: Average Section TSRST Curves Sorted by Air Void Content (FMLC) (Red = 4% Air Voids, Blue = 8% Air Voids, Black = 12% Air Voids)

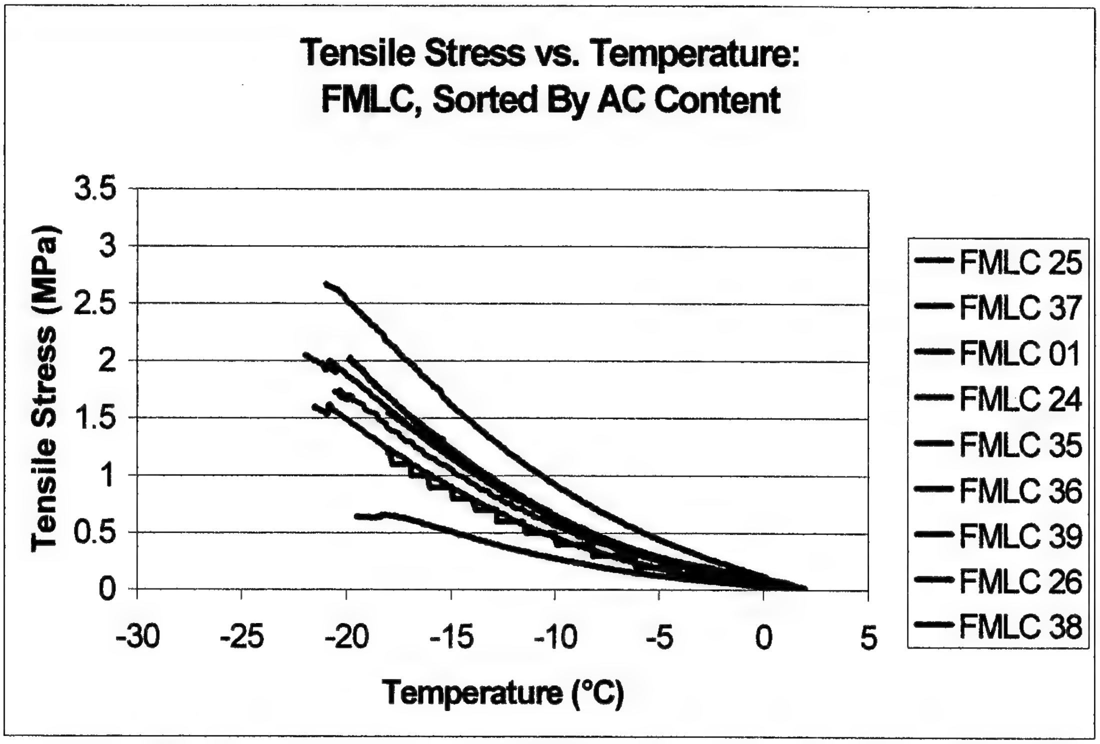


Figure 3-12: Average Section TSRST Curves Sorted by AC Content (FMLC) (Red = High AC Content, Blue = Medium AC Content, Black = Low AC Content)

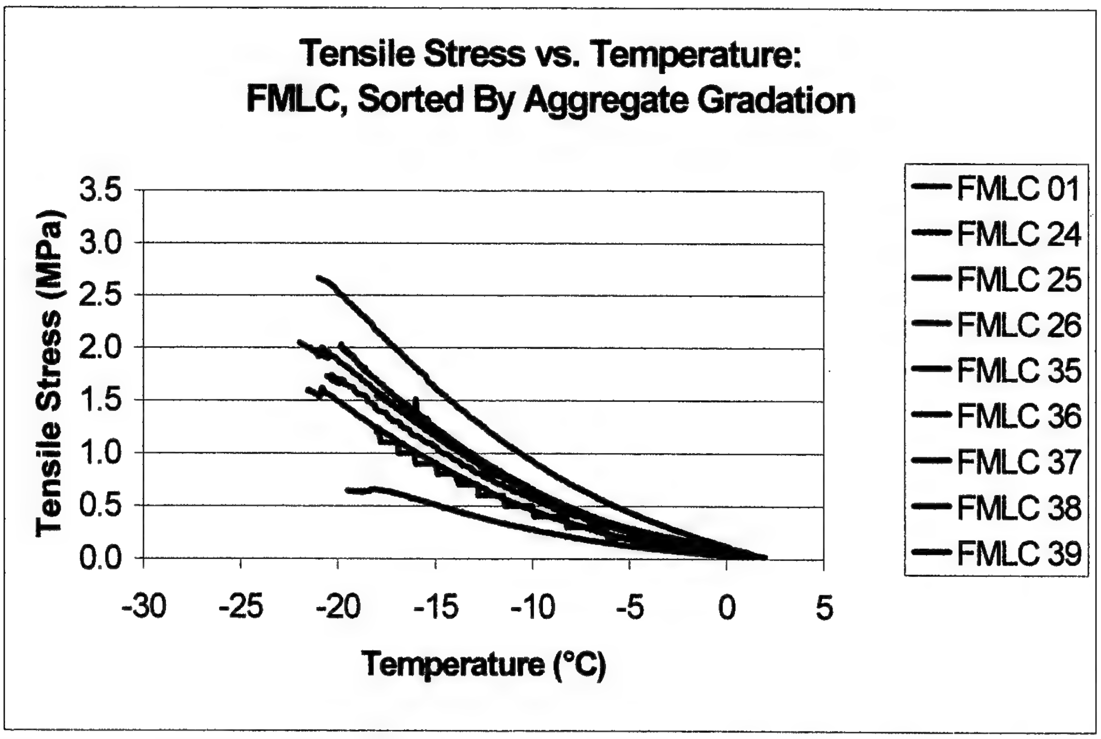


Figure 3-13: Average Section TSRST Curves Sorted by Aggregate Gradation (FMLC) (Red = Fine Aggregate Gradation, Black = Coarse Aggregate Gradation)

Based on Figures 3-11, 3-12, and 3-13, no single variable appears to dominate loading rate.

3.2.4 Statistical Analysis and Discussion

To analyze the FMLC temperature data a correlation matrix was constructed showing the strength of relationships between input variables and fracture temperature (See Table 3-8).

FMLC Correlation Coefficient Matrix					
	Fracture Temp	% Air Voids	Age Cond	% AC Cont	Agg Grad
Fracture Temp	1.00				
% Air Voids	0.04	1.00			
Age Cond					
% AC Cont	-0.35	-0.47		1.00	
Agg Grad	0.30	-0.39		0.20	1.00

Table 3-8: FMLC Correlation Matrix

As shown in the correlation matrix, there are no strong relationships between input variables and sample fracture temperature. There appears to be a slight relationship between % asphalt content (-.35) and fracture temperature, but this is highly suspect due to the small number of samples tested. The results of this correlation matrix seem to underscore the insignificant differences between average fracture temperature versus individual mix variables from Table 3-7.

Overall, the FMLC fracture temperature data fails to present any single mix or compaction variable which controls low temperature cracking.

3.3 LMLC

Sixty LMLC short and long-term aged TSRST samples were tested in this experiment. Following testing, one sample was discarded due to compaction flaws leaving a total of fifty-nine. Thirty of these samples were short-term aged and twenty-nine were short and long-term aged. Likewise, twenty-nine of these samples were fabricated using the fine aggregate gradation and thirty were fabricated using the coarse aggregate gradation. Also considered in this experiment was AC content and air void content (See Table 3-9).

Long and short-term aged LMLC samples from the same WesTrack sections have been broken into separate groups to simplify the study of aging effects. For example, Section 01 was broken into two sections identified as section 01S for short-term aged and 01L for long-term aged samples.

Coarse Aggregate Gradation - Short-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (5.0%)		LMLC (3)	LMLC (3)
Medium (5.7%)	LMLC (3)	LMLC (3)	LMLC (3)
High (6.4%)	LMLC (3)	LMLC (3)	

Coarse Aggregate Gradation - Long-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (5.0%)		LMLC (3)	LMLC (3)
Medium (5.7%)	LMLC (3)	LMLC (3)	LMLC (3)
High (6.4%)	LMLC (3)	LMLC (3)	

Fine Aggregate Gradation - Short-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (4.7%)		LMLC (3)	LMLC (3)
Medium (5.4%)	LMLC (3)	LMLC (3)	LMLC (3)
High (6.1%)	LMLC (3)	LMLC (3)	

Fine Aggregate Gradation - Long-Term Age

Asphalt Content (% by weight of mix)	Air Content (% by Volume)		
	Low (4%)	Med (8%)	High (12%)
Low (4.7%)		LMLC (3)	LMLC (3)
Medium (5.4%)	LMLC (3)	LMLC (2)	LMLC (3)
High (6.1%)	LMLC (3)	LMLC (3)	

Notes: 1) Number next to identifier in # indicates quantity of samples to be tested for that particular mix.
2) Blacked out cells were not included in this experiment because of obvious difficulty in achieving these combinations.

Table 3-9: LMLC Test Data

The LMLC portion of this experiment was the most comprehensive of the three fabrication methods tested. Therefore, the conclusions drawn should be given greater consideration when compared to the FMFC or the FMLC portions of this study.

3.3.1 Air Void Content

Air void contents of LMLC TSRST samples were controlled very tightly. Finished samples were allowed only a $\pm$ 1% tolerance from target void contents to be considered usable. The average air void range for all low air void sections (4.0% target) was 4.0% to 4.8%. For the medium air void sections (8.0% target) the range was 8.0% to 8.5%. The average air void range for the high air void section (12.0% target) was 12.1% to 12.8% (See Figure 3-14).

3.3.2 Fracture Temperature

See Table 3-10 for a summary of average LMLC section fracture temperatures. A graphical representation of the same data is shown in Figure 3-15.

Sample fracture temperatures for the LMLC portion of this study ranged from -19.0° C to -33.6° C with section 03L having the highest overall average fracture temperature at -22.2° C. Samples fabricated with the fine aggregate gradation had a fracture temperature range of -19.0° C to -33.6° C with an average of -26.2° C, while samples fabricated with the coarse aggregate gradation had a range of -21.5° C to -32.4° C with an average of -26.4° C. The average difference in fracture temperature between the two gradations was 0.2° C.

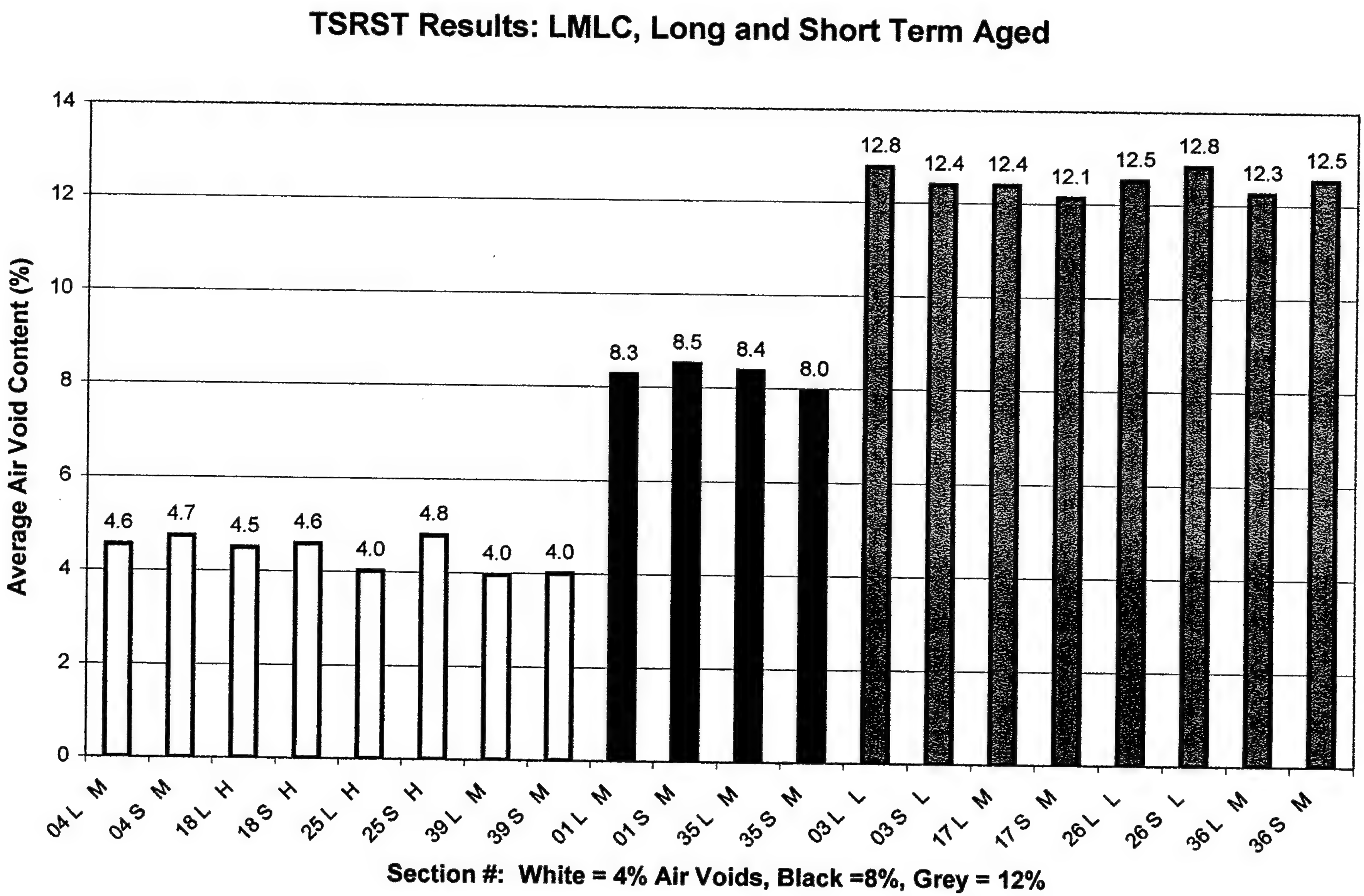


Figure 3-14: Average Section Air Void Contents (LMLC)

Westrack Project: Summary of TSRST Data Lab Mixed Lab Compacted, Long- and Short-Term Aged						
Section / AC Content	Average Void Content	Average Tensile Strength		Average Fracture Temperature		
	(%)	(MPa)	(psi)	^{0}C	^{0}F	
04 L M	4.6	3.23	468	-25.1	-13.3	Average Change in Fracture Temperature From Long-To Short-Term Age (°C) -2.8
04 S M	4.7	2.89	419	-29.2	-20.5	
18 L H	4.5	2.94	427	-23.2	-9.8	
18 S H	4.6	3.08	447	-28.3	-18.9	Average Change in Fracture Temperature From Low To High AC Content (°C) -1.9
25 L H	4.0	2.98	433	-27.1	-16.7	
25 S H	4.8	3.02	438	-26.9	-16.4	
39 L M	4.0	3.31	480	-25.0	-13.0	
39 S M	4.0	3.42	496	-27.6	-17.6	
01 L M	8.3	2.45	355	-23.7	4.6	
01 S M	8.5	2.16	313	-28.0	-18.3	Average Change in Fracture Temperature From High To Low Air Voids (°C) -.05
35 L M	8.4	2.58	374	-26.0	-14.8	
35 S M	8.0	2.70	392	-27.1	-16.9	
03 L L	12.8	1.33	192	-22.2	-8.0	
03 S L	12.4	1.72	249	-27.5	-17.5	
17 L M	12.4	1.84	266	-26.2	-15.1	Average Change in Fracture Temperature From Fine To Coarse Aggregate Gradation (°C) -0.2
17 S M	12.1	1.90	275	-28.5	-19.2	
26 L L	12.5	2.05	298	-24.8	-12.7	
26 S L	12.8	1.99	288	-24.9	-12.9	
36 L M	12.3	2.27	329	-25.8	-14.4	
36 S M	12.5	2.24	324	-29.0	-20.2	

Table 3-10: LMLC Data Summary

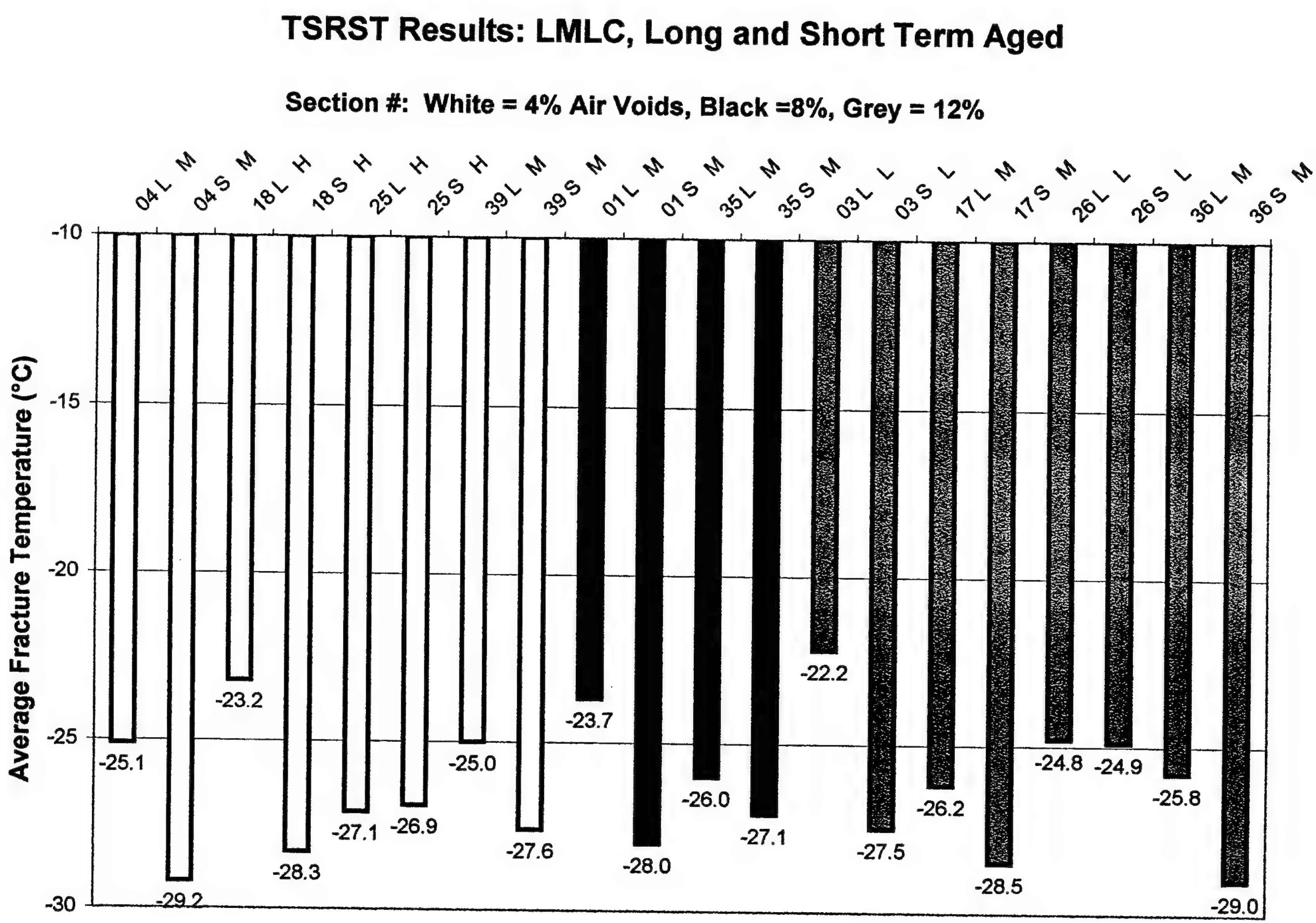


Figure 3-15: Average Section Fracture Temperatures (LMLC)

Samples fabricated with low, medium, and high AC contents had fracture temperature ranges of -20.2° C to -28.3° C, -22.0° C to -33.6° C, and -19.0° C to -32.4° C, respectively. The average fracture temperatures for the low, medium, and high AC content samples were -24.9° C, -26.8° C, and -26.4° C, respectively. The total difference between the high and low average was 1.9° C.

Samples fabricated with low, medium, and high air void contents had fracture temperature ranges of -19.0° C to -33.6° C, -22.0° C to -30.1° C, and -20.2° C to -30.5° C, respectively. The average fracture temperatures for the low, medium, and high air void content samples were -26.6° C, -26.2° C, and -26.1° C, respectively. The total difference between the high and the low average was 0.5° C.

The range of fracture temperatures for short-term aged samples was -21.5° C to -33.6° C with an average fracture temperature of -27.7° C. Long-term aged samples had a fracture temperature range of -19.0° C to -32.4° C with an average fracture temperature of -24.9° C. The average difference in fracture temperature between samples long-term aged and samples short-term aged was 2.8° C. See Table 3-11 for a summary of average results versus mixing and compaction variables.

LMLC TSRST Average Fracture Temperature Results							
Mix or Comaction Variable / Sample Averages							
Air Void Content	Sample Averages (°C)	AC Content	Sample Averages (°C)	Agg Gradation	Sample Averages (°C)	Age Condition	Sample Averages (°C)
Low	-26.6	Low	-24.9	Fine	-26.2	Short	-27.7
Medium	-26.2	Medium	-26.8	Coarse	-26.4	Long	-24.9
High	-26.1	High	-26.4				
Minimum	-26.1	Minimum	-24.9	Minimum	-26.2	Minimum	-24.9
Maximum	-26.6	Maximum	-26.8	Maximum	-26.4	Maximum	-27.7
Difference	0.5	Difference	1.9	Difference	0.2	Difference	2.8

Table 3-11: LMLC Average Fracture Temperature Results Versus Mixing and Compaction Variables

3.3.3 Fracture Strengths and Loading Rates

The fracture strength data generated from the LMLC TSRST portion of this experiment are summarized in Table 3-10 and Figure 3-16. The WesTrack section demonstrating the lowest average fracture strength was section 03L with an average of only 1.33 MPa. The section with the highest average fracture strength was section 39S with an average of 3.42 MPa.

Sample loading rates, or the slope of the stress versus temperature curves for individual LMLC TSRST samples along with sample fracture strengths and temperatures are found in Appendix F. Average stress versus temperature curves depicting relationships between air void content, AC content, aggregate gradation, and age conditioning for each LMLC WesTrack section are shown in Figures 3-17, 3-18, 3-19, and 3-20. In these figures, average WesTrack section curves are sorted by air void content, AC content, aggregate gradation, and age conditioning to show their effects on loading rate.

Figure 3-17 indicates there is a relationship between air void content and sample loading rate. Samples with low air voids are clustered towards the top of the graph indicating a more rigid sample structure that is sensitive to decreasing temperatures. Samples with high air void contents are clustered near the bottom of the group of curves indicating asphalt concrete structures that are not greatly affected by decreasing temperatures. As expected, samples with medium air void contents are scattered between the low and the high air void content samples.

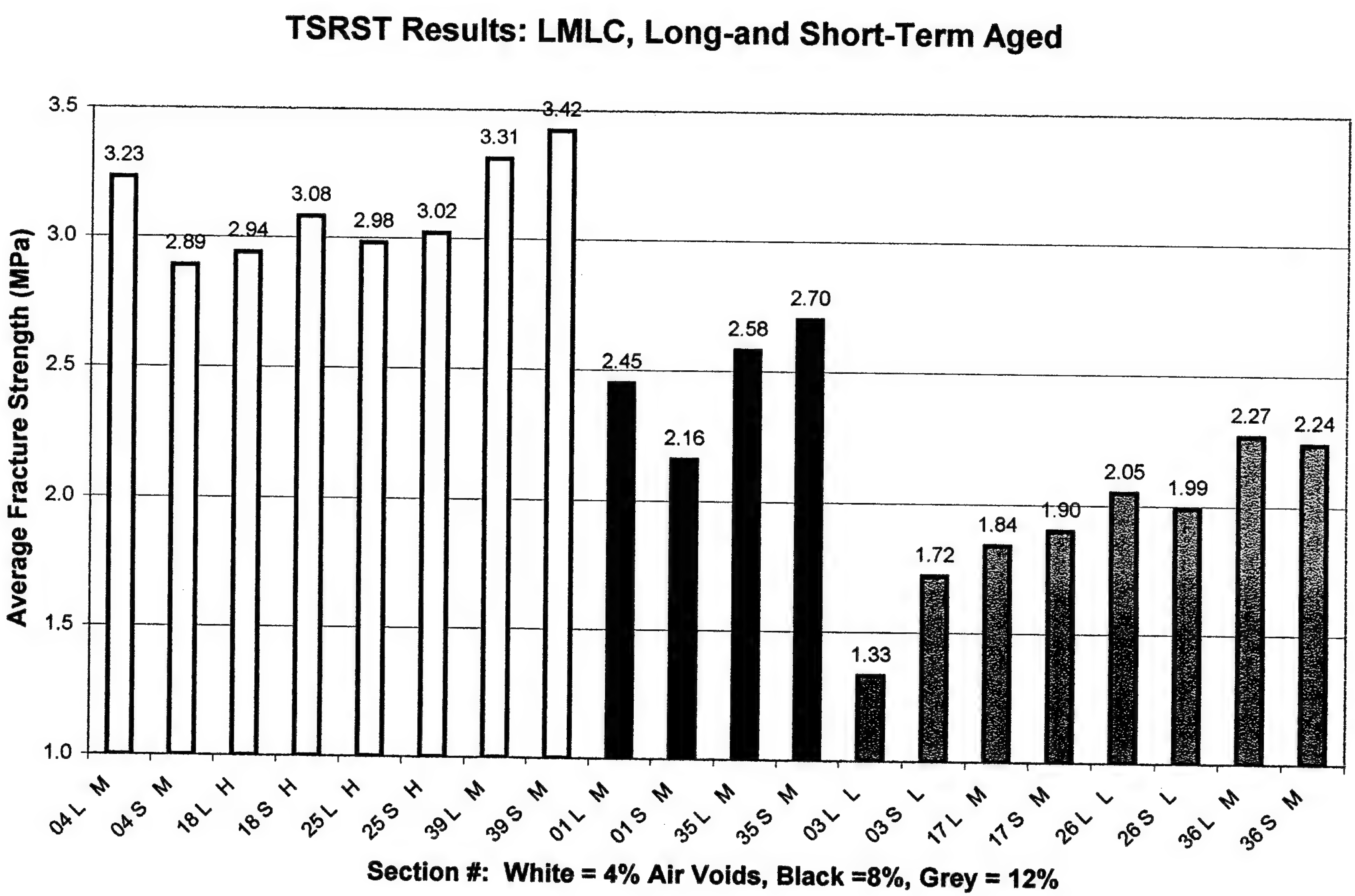


Figure 3-16: Average Section Fracture Strengths (LMLC)

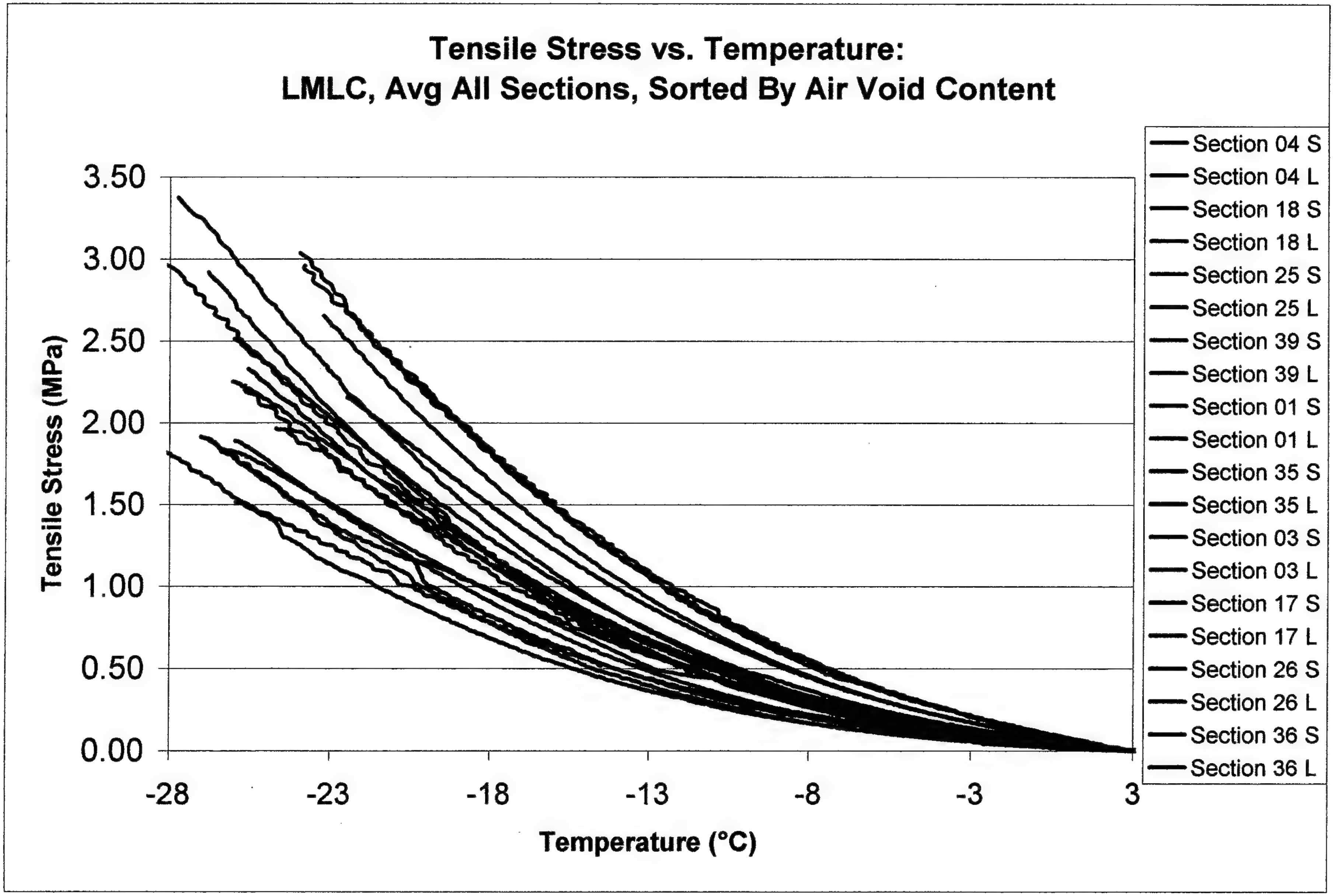


Figure 3-17: Average Section TSRST Curves Sorted by Air Void Content (LMLC)
(Red = Low Air Void Content, Blue = Medium Air Void Content, Black = High Air Void Content)

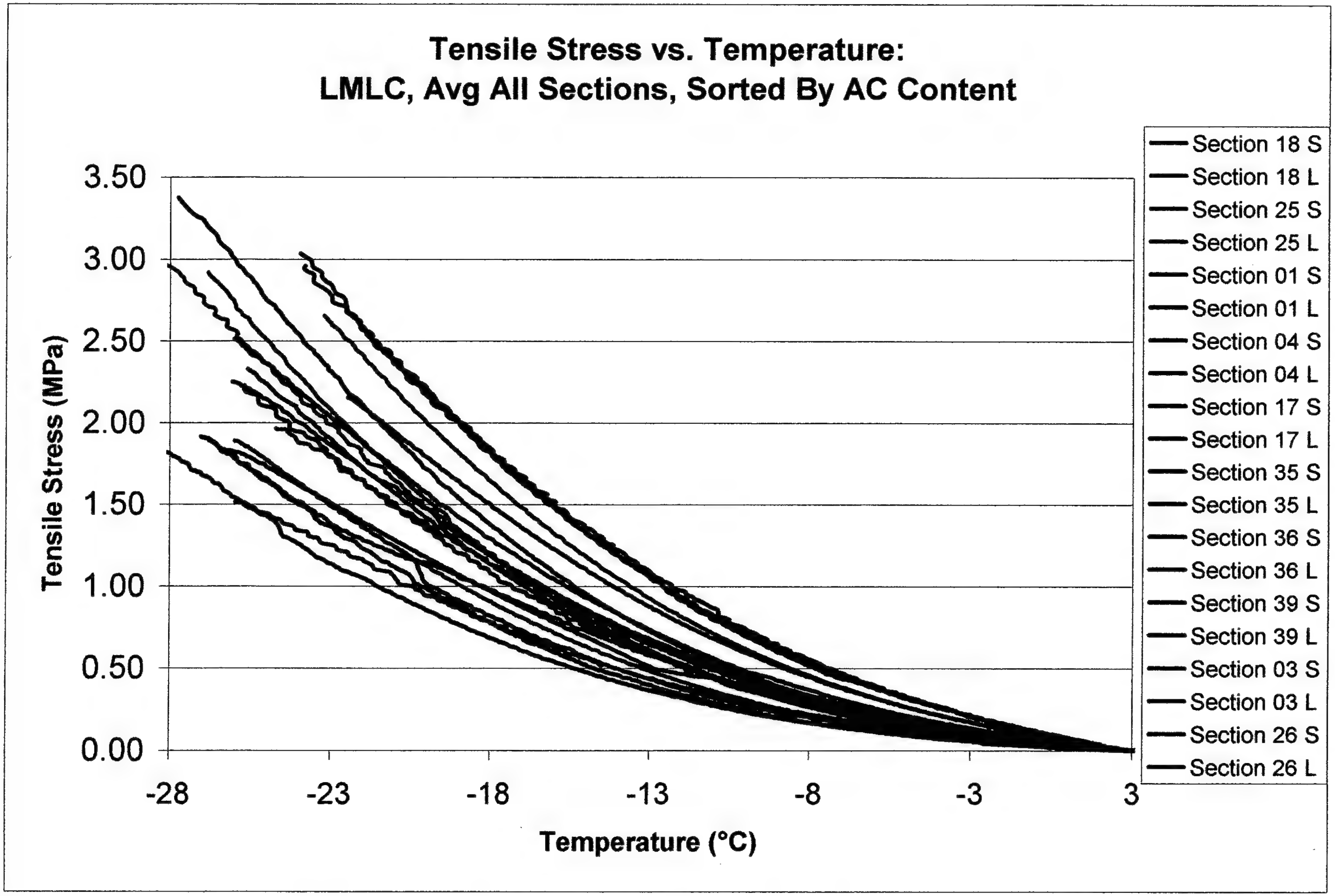


Figure 3-18: Average Section TSRST Curves Sorted by AC Content (LMLC)
(Red = High AC Content, Blue = Medium AC Content, Black = Low AC Content)

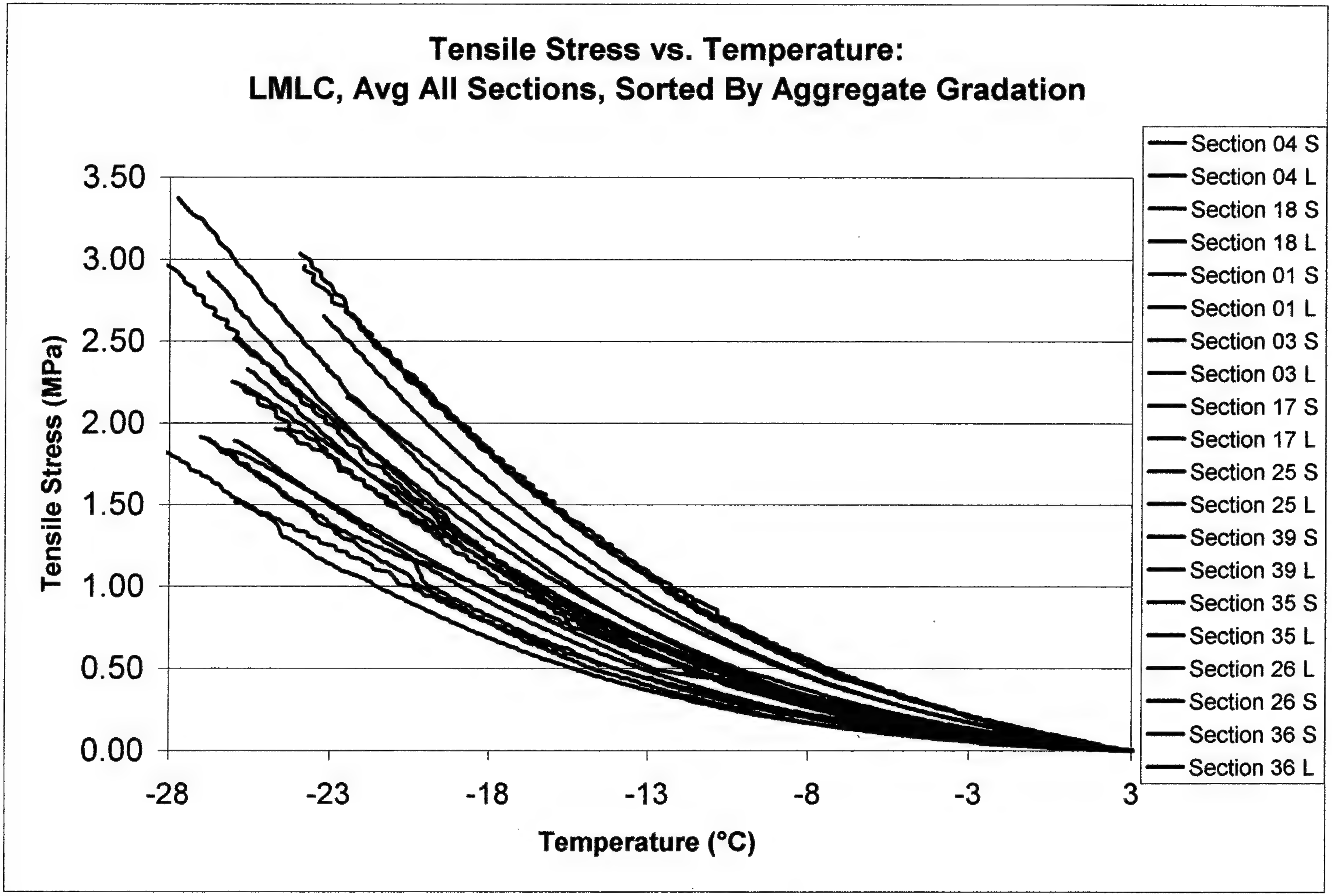


Figure 3-19: Average Section TSRST Curves Sorted by Aggregate Gradation (LMLC)
(Red = Fine Aggregate Gradation, Black = Coarse Aggregate Gradation)

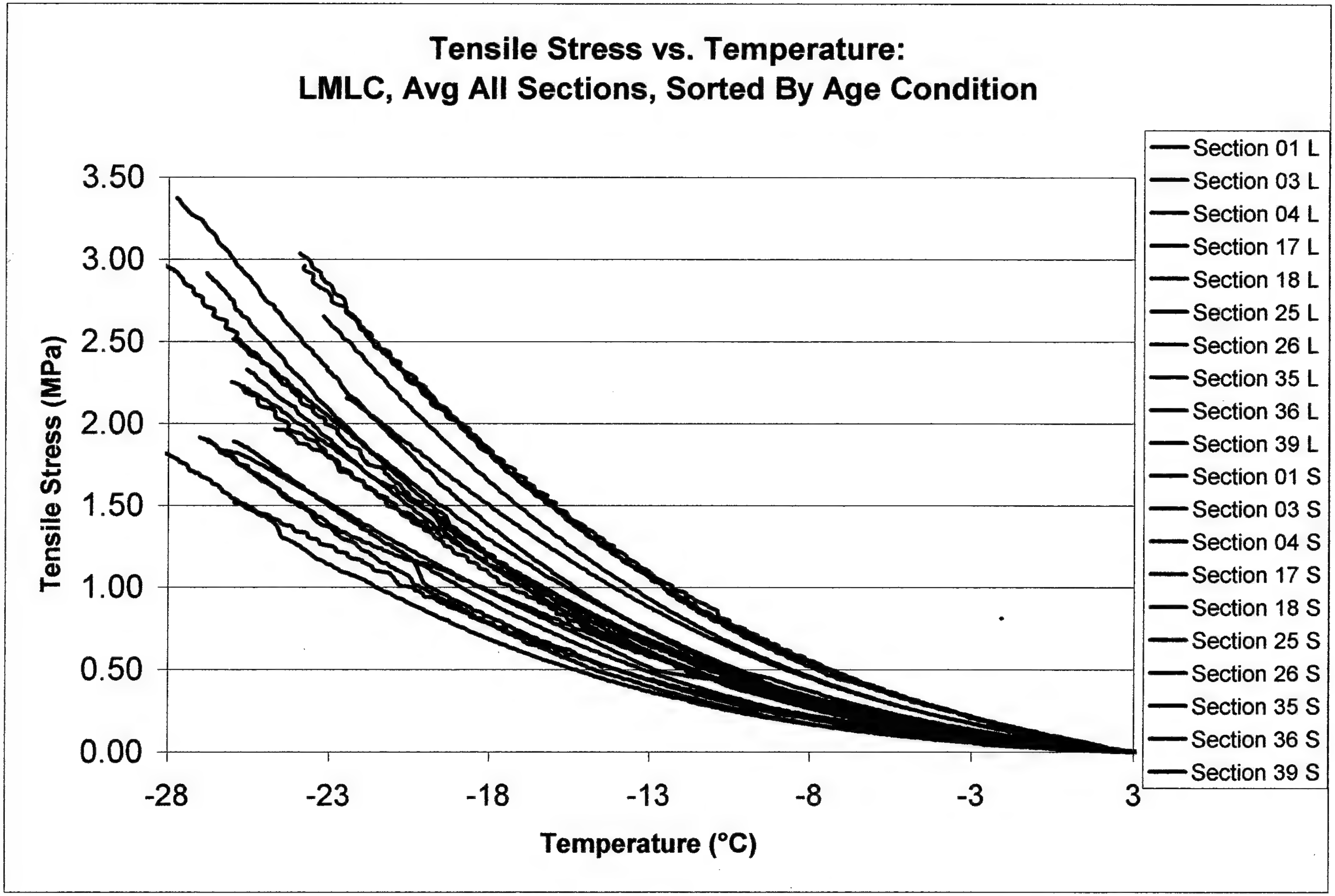


Figure 3-20: Average Section TSRST Curves Sorted by Age Condition (LMLC)
(Red = Long Term Aged, Black = Short Term Aged)

In Figure 3-18 stress vs. temperature curves were distributed with high AC content samples loading at the highest rate, followed by medium AC content samples and low AC content samples. The distribution of loading curves in Figure 3-17 was very similar to Figure 3-18 with high AC content samples loading most quickly followed by medium AC and finally low AC content samples. The similarity in the data is attributed to the relationship between air void content and AC content that was built into the experiment design. Samples fabricated with a high AC content were all compacted to low air void specifications. Samples fabricated with a low AC content were all compacted to high air void specifications. The nature of this relationship indicates samples were properly mixed and compacted to experiment specifications.

The distribution of curves in Figure 3-19 appears to be random with respect to aggregate gradation. This observation indicates that there is little, if any influence of aggregate gradation on tensile stresses and fracture.

Figure 3-20 presents an obvious pattern showing long-term aged samples loading consistently faster than short-term aged samples. This suggests that age conditioning of asphalt concrete has a direct effect on the expected loading rate of asphalt concrete subject to decreasing temperatures.

3.3.4 Statistical Analysis and Discussion

To analyze the LMLC temperature data a correlation matrix was constructed showing the strength of relationships between input variables and fracture temperature (See Table 3-12).

LMLC Correlation Coefficient Matrix					
	Fracture Temp	% Air Voids	Age Cond	% AC Cont	Agg Grad
Fracture Temp	1.00				
% Air Voids	0.08	1.00			
Age Cond	-0.54	0.01	1.00		
% AC Cont	-0.18	-0.68	-0.01	1.00	
Agg Grad	-0.03	-0.02	-0.02	0.32	1.00

Table 3-12: LMLC Correlation Matrix

The input variable most strongly correlated to fracture temperature is age conditioning (-.54). This correlation underscores the difference in average fracture temperatures for long-versus short-term aging found in table 3-11. The correlation coefficient for AC content (-.18) indicates that there is a weak connection between AC content and sample fracture temperature similar to the results found in table 3-11.

From the fracture temperature data gathered for LMLC samples, age conditioning is the greatest single contributor to low temperature cracking potential. Samples long-term aged fractured on average 2.8° C warmer than samples short-term aged.

3.4 Experiment Data Analysis and Discussion

The data analyzed in this section includes all three data sets discussed earlier (FMFC, FMLC, and LMLC). See Appendix G for a summary of all sample (FMFC, FMLC, LMLC) fracture temperatures, fracture strengths, air voids, AC contents, aggregate gradations, and age conditions.

3.4.1 Results (FMFC vs. FMLC vs. LMLC)

3.4.1.1 Air Void Contents

Overall, sample air voids conformed to experiment specifications well. LMLC samples were all within $\pm$ 1% of target air voids while FMFC and FMLC samples were with in $\pm$ 3%. All three air void levels low, medium, and high were well represented in the experiment, with the exception of high air void content samples from the FMFC and FMLC methods (See Figure 3-21 and Table 3-13). Using lab compaction techniques, it was possible to obtain asphalt concrete samples with air void contents similar to those created in the field using commercial compaction equipment.

3.4.1.2 Fracture Temperatures

Fracture temperatures of the LMLC samples were consistently lower than either the FMFC or the FMLC samples. Comparing sections with samples fabricated using all three methods, LMLC samples fractured on average 4.0° C lower than FMFC samples and 5.5° C lower than FMLC samples. Potential reasons for these differences are mix variation, differences in compaction mechanisms (field vs. lab compacted), and time at elevated mixing/compaction temperatures. LMLC samples were heated only one time above 110° C for approximately 5 hours to facilitate mixing and compaction. Similarly, FMFC samples were also heated only one time above 110° C for approximately 5-6 hours. FMLC samples on the other hand, were heated once during field mixing for 4-5 hours and again in the laboratory for 5 hours prior to compaction. Average section fracture temperatures are summarized in Table 3-13 and Figure 3-22.

Summary of Overall TSRST Data

Section / AC Content	Average Void Content			Average Tensile Strength						Average Fracture Temperature					
	(%)			(MPa)			(psi)			(°C)			(°F)		
	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC
01 S M	9.10	9.00	8.50	1.81	1.47	2.16	262	213	313	-18.5	-24.0	-28.0	-1.2	-11.2	-18.3
01 L M	-	-	8.30	-	-	2.45	-	-	355	-	-	-23.7	-	-	-10.6
03 S L	-	-	12.40	-	-	1.72	-	-	249	-	-	-27.5	-	-	-17.5
03 L L	-	-	12.80	-	-	1.33	-	-	192	-	-	-22.2	-	-	-8.0
04 S M	-	-	4.70	-	-	2.89	-	-	419	-	-	-29.2	-	-	-20.5
04 L M	-	-	4.60	-	-	3.23	-	-	468	-	-	-25.1	-	-	-13.3
17 S M	-	-	12.10	-	-	1.90	-	-	275	-	-	-28.5	-	-	-19.2
17 L M	-	-	12.40	-	-	1.84	-	-	266	-	-	-26.2	-	-	-15.1
18 S H	-	-	4.60	-	-	3.08	-	-	447	-	-	-28.3	-	-	-18.9
18 L H	-	-	4.50	-	-	2.94	-	-	427	-	-	-23.2	-	-	-9.8
24 S M	4.50	4.90	-	2.98	2.20	-	432	320	-	-23.2	21.3	-	-9.8	-6.3	-
25 S H	2.60	3.00	4.80	2.88	2.54	3.02	417	369	438	-21.3	-23.5	-26.9	-6.3	-10.3	-16.4
25 L H	-	-	4.00	-	-	2.98	-	-	433	-	-	-27.1	-	-	-16.7
26 S L	8.40	6.90	12.80	2.35	0.61	1.99	341	89	288	-20.8	-18.3	-24.9	-5.5	-6.2	-12.9
26 L L	-	-	12.50	-	-	2.05	-	-	298	-	-	-24.8	-	-	-12.7
35 S M	8.00	7.80	8.00	1.95	2.14	2.70	283	311	392	-25.8	-22.2	-27.1	-14.5	-7.9	-16.9
35 L M	-	-	8.40	-	-	2.58	-	-	374	-	-	-26.0	-	-	-14.8
36 S M	12.40	7.60	12.50	1.16	2.20	2.24	168	319	324	-28.7	-21.3	-29.0	-19.7	-6.3	-20.2
36 L M	-	-	12.30	-	-	2.27	-	-	329	-	-	-25.8	-	-	-14.4
37 S H	9.10	7.60	-	1.80	2.07	-	262	300	-	-24.3	-22.7	-	-11.8	-8.9	-
38 S L	7.20	8.10	-	2.54	2.72	-	369	394	-	-26.8	-21.3	-	-16.2	-6.3	-
39 S M	3.90	8.10	4.00	2.98	1.66	3.42	433	240	496	-24.6	-21.2	-27.6	-12.2	-6.2	-17.6
39 L M	-	-	4.00	-	-	3.31	-	-	480	-	-	-25.0	-	-	-13.0

Table 3-13: Data Summary (FMFC, FMLC, LMLC)

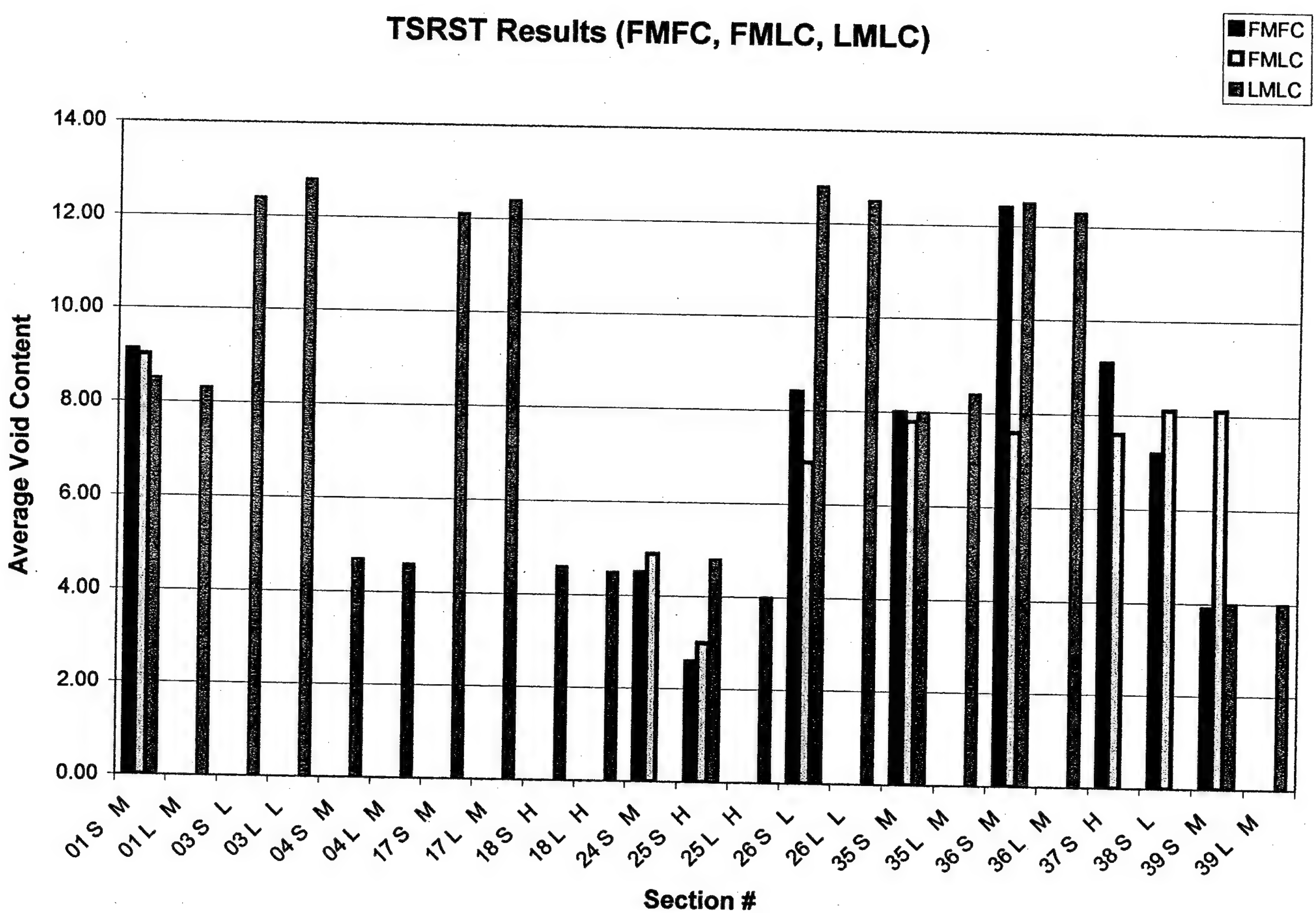


Figure 3-21: Average Section Air Void Contents (FMFC, FMLC, LMLC)

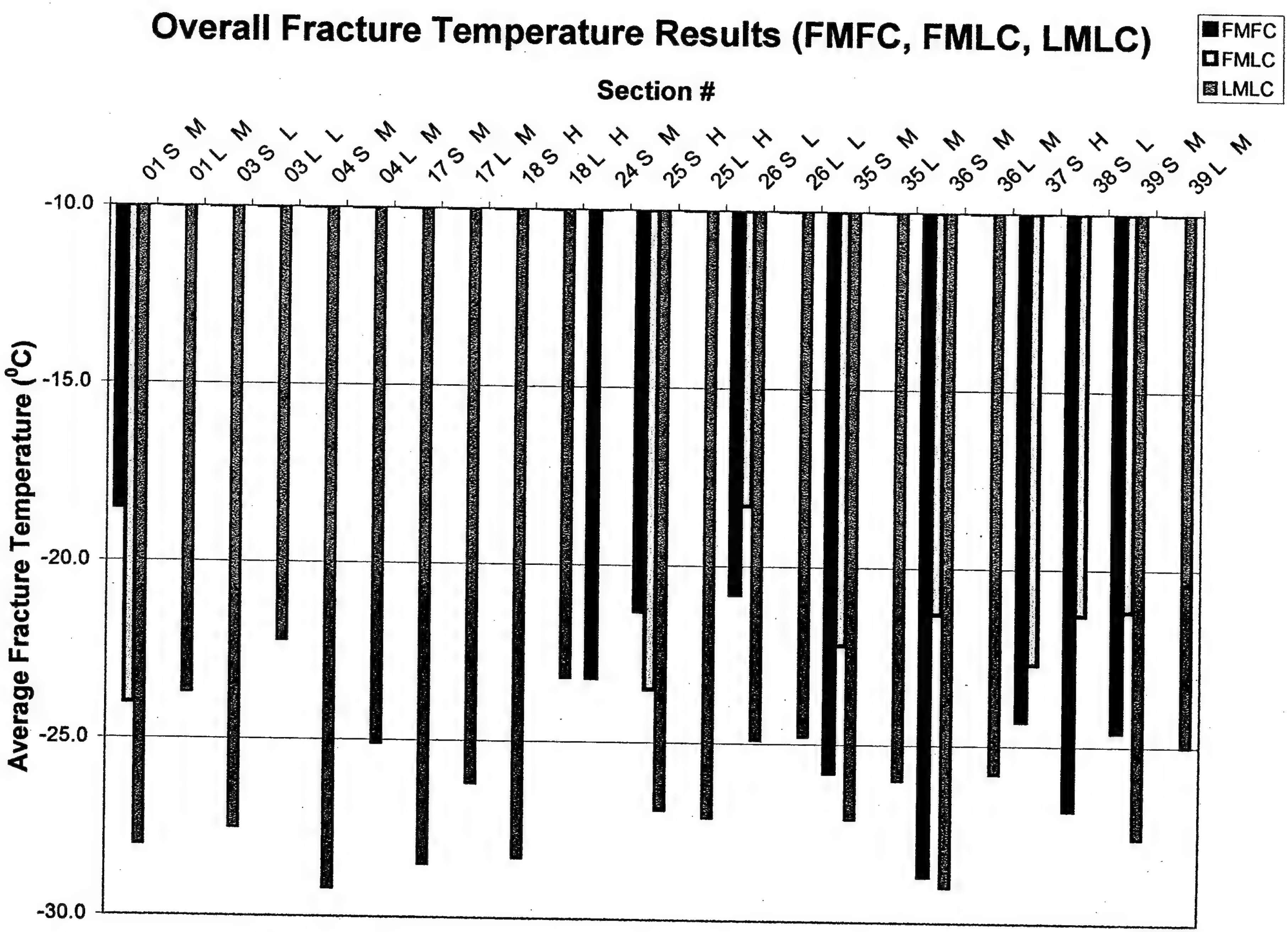


Figure 3-22: Average Section Fracture Temperatures (FMFC, FMLC, LMLC)

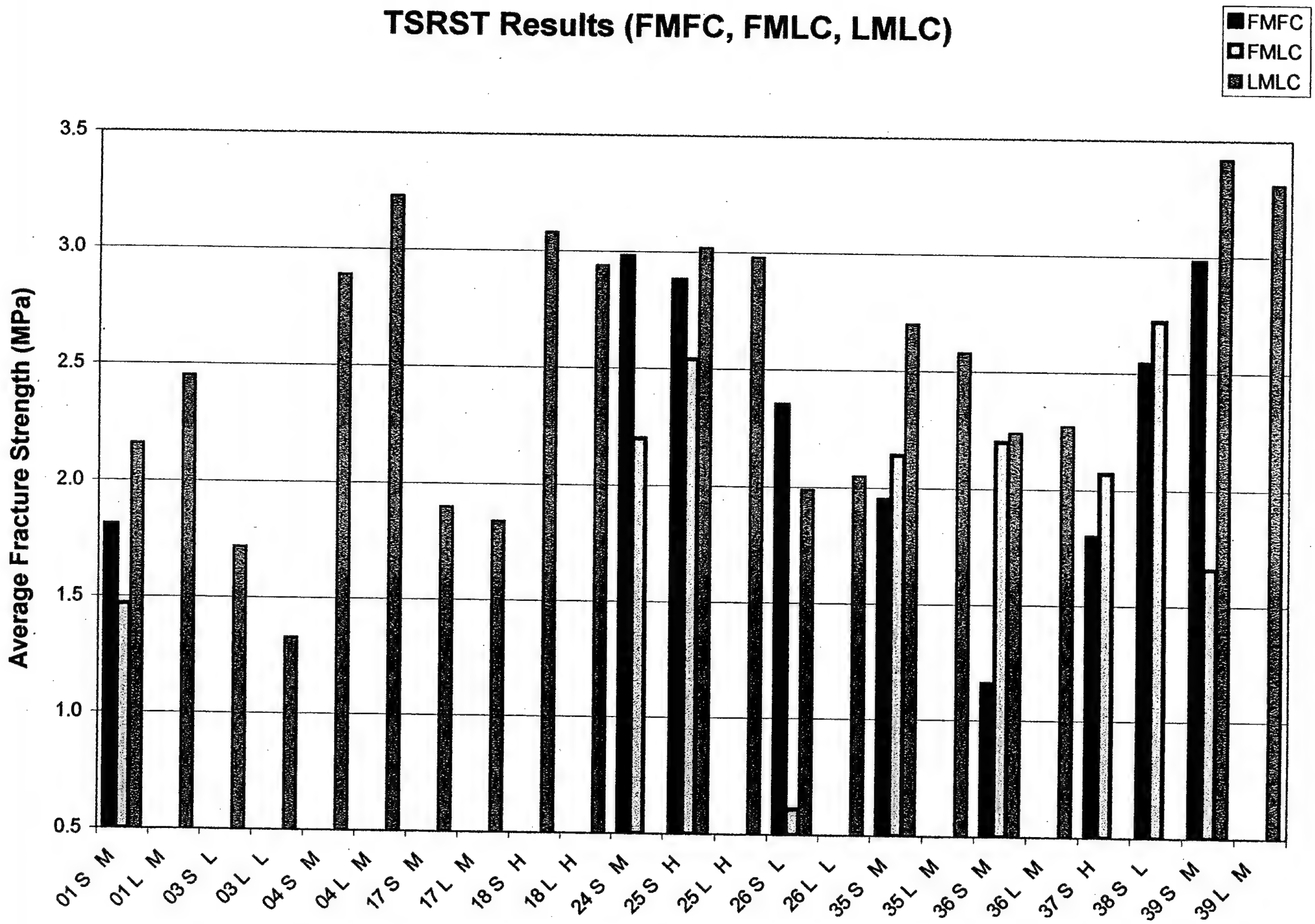


Figure 3-23: Average Section Fracture Strengths (FMFC, FMLC, LMLC)

3.4.1.3 Fracture Strength

The fracture strengths of LMLC samples were consistently higher than either the FMFC or the FMLC samples. Comparing WesTrack sections with samples fabricated using all three methods, the fracture strengths of LMLC samples were on average 0.4 MPa greater than FMFC samples and 0.8 MPa greater than FMLC samples. Potential reasons for these differences are mix variation, differences in compaction mechanisms (field vs. lab compacted), and time at elevated mixing/compaction temperatures. LMLC samples were heated only one time above 110° C for approximately 5 hours to facilitate mixing and compaction. Similarly, FMFC samples were also heated only one time above 110° C for approximately 5-6 hours. FMLC samples on the other hand, were heated once during field mixing for 4-5 hours and again in the laboratory for 5 hours prior to compaction. Average section fracture strengths are summarized in Table 3-13 and Figure 3-23.

3.4.2 Effects of Mix/Compaction Variables on Low Temperature Cracking

See Table 3-13 for a summary of overall (FMFC, FMLC, LMLC) average section fracture temperatures. A graphical representation of the same data is found in Figure 3-22.

Sample fracture temperatures for this study ranged from -13.3° C to -35.0° C with section 26S having the highest overall average fracture temperature at -21.3° C. Samples fabricated with the fine aggregate gradation had a fracture temperature range of -16.1° C to -33.6° C with an average of -25.5° C, while samples fabricated with the coarse

aggregate gradation had a range of -13.3° C to -35.0° C with an average of -24.3° C. The average difference between the two gradations was 1.2° C.

Samples fabricated with low, medium, and high AC contents had fracture temperature ranges of -13.3° C to -28.3° C, -16.1° C to -35.0° C, and -19.0° C to -32.4° C, respectively. The average fracture temperatures for the low, medium, and high AC content samples were -23.4° C, -24.8° C, and -24.7° C, respectively. The difference between the high and low average was 1.4° C.

Samples fabricated with low, medium, and high air void contents had fracture temperature ranges of -19.0° C to -33.6° C, -16.1° C to -30.1° C, and -13.3° C to -35.0° C, respectively. The average fracture temperatures for the low, medium, and high air void content samples were -25.3° C, -23.4° C, and -24.8° C, respectively. The difference between the high and the low average was 1.9° C.

The range of fracture temperatures for samples short-term aged was -13.3° C to -35.0° C with an average fracture temperature of -24.3° C. Samples long-term aged had a fracture temperature range of -19.0° C to -32.4° C with an average fracture temperature of -24.9° C. The average difference in fracture temperature between samples long-term aged and samples short-term aged was 0.6° C. See Table 3-14 for a summary of average results versus mix parameters and compaction variables.

3.4.2.1 Fracture Temperature Statistical Analysis

Fracture temperature coefficients of variation for each mix / compaction variable are summarized in Table 3-15.

Overall (FMFC, FMFC, LMLC) TSRST Average Fracture Temperature Results							
Mix or Compaction Variable / Sample Averages							
Air Void Content	Sample Averages (°C)	AC Content	Sample Averages (°C)	Agg Gradation	Sample Averages (°C)	Age Condition	Sample Averages (°C)
Low	-25.3	Low	-23.4	Fine	-25.5	Short	-24.3
Medium	-23.4	Medium	-24.8	Coarse	-24.3	Long	-24.9
High	-24.8	High	-24.7				
Minimum	-23.4	Minimum	-23.4	Minimum	-24.3	Minimum	-24.3
Maximum	-25.3	Maximum	-24.8	Maximum	-25.5	Maximum	-24.9
Difference	**1.9**	**Difference**	**1.4**	**Difference**	**1.2**	**Difference**	**0.6**

Table 3-14: Overall Average Fracture Temperature Results vs. Mixing and Compaction Variables

Fracture Temperature Coefficient of Variation (%)								
	Fabrication Method							
	FMFC		FMLC		LMLC		Combined (FMFC, FMLC, LMLC)	
	# of Samples	C. V.	# of Samples	C. V.	# of Samples	C. V.	# of Samples	C. V.
Coarse Aggregate Gradation	24	12.9	24	11.0	30	7.9	78	13.6
Fine Aggregate Gradation	6	13.7	3	15.7	29	11.3	38	16.1
Low AC Content	6	12.7	6	16.7	12	10.1	24	15.2
Medium AC Content	18	20.0	15	10.3	35	7.9	68	14.5
High AC Content	6	8.7	6	6.7	12	12.0	24	12.5
Low Air Void Content	6	9.1	6	7.6	24	10.9	36	12.5
Medium Air Void Content	18	16.4	15	10.6	11	7.4	44	14.4
High Air Void Content	6	20.5	6	16.3	24	9.6	36	15.9
Short-Term Aged	30	16.7	27	11.0	30	7.2	87	16.0
Long-Term Aged	0		0		29	9.3	29	9.3

Table 3-15: Fracture Temperature Coefficients of Variation

The LMLC coefficients of variation (CV) in the majority of cases are lower than those calculated for the FMFC or the FMLC samples. When all data are combined, the CVs increase significantly.

The strength of relationships between fracture temperature and experiment input variables were determined by constructing a correlation matrix (See Table 3-16).

LMLC, FMLC, FMFC Correlation Matrix					
	Fracture Temp	% Air Voids	Age Cond	% AC Cont	Agg Grad
Fracture Temp	1.00				
% Air Voids	-0.10	1.00			
Age Cond	0.08	-0.10	1.00		
% AC Cont	-0.09	-0.54	0.06	1.00	
Agg Grad	0.07	-0.17	0.19	0.30	1.00
% Air Voids*Agg Grad	-0.08				
Age Cond*Agg Grad	0.13				
% AC Cont*Agg Grad	0.04				
% AC Cont*Age Cond	0.05				
% AC Cont*% Air Voids	-0.14				
% Air Voids*Age Cond	-0.07				

Table 3-16: (FMFC, FMLC, LMLC) Correlation Matrix

Table 3-16 indicates that there is no strong relationship between any single mix parameter and/or compaction variable and fracture temperature.

3.4.3 Fracture Temperature Prediction Model

Using the fracture temperature data generated from this experiment, a multiple regression analysis was performed to develop a numerical prediction model. Independent

and dependent variables are defined in Table 3-17. Table 3-18 summarizes the results of this analysis.

Independent Variables	
% AC Content = %AC	High Medium Low
% Air Void Content = %Air	High Medium Low
Aggregate Gradation = Agg	Fine Coarse
Age Conditioning = Age	Short Long
Dependant Variable	
Fracture Temperature = FT	

Table 3-17: Independent and Dependent Regression Variables

Table 3-18 along with Table 3-16 indicate that a significant prediction model can not be derived from the fracture temperature data generated in this study. There were no significant correlations between any of the independent variables and sample fracture temperatures. The model yielding the highest explained variation ($R^2 = .0869$) was a function of (%AC, %Air, Agg, Age, Age*Agg, Age*%Air, and Age*%AC). At this level of significance, the prediction models must be discarded.

Multiple Regression Fracture Temperature Prediction Model	
FT = f( )	Model R^2
%AC	0.0086
Agg	0.0056
%Air	0.0109
Age	0.0059
%AC, Agg	0.0201
%AC, %Air	0.0423
%AC, Age	0.0153
Agg, %Air	0.0142
Agg, Age	0.0096
Age, %Air	0.0154
%AC, Agg, %Air	0.0532
%AC, Agg, Age	0.0241
%AC, %Air, Age	0.0469
Agg, %Air, Age	0.0175
%AC, Agg, %Air, Age	0.0557
%AC, Agg, %Air, Age, Agg*Age	0.0807
%AC, Agg, %Air, Age, Agg*Age, %AC*%Air, %AC*Agg	0.0812
%AC, Agg, %Air, Age, Age*Agg, Age*%AC, Age*%Air	0.0869

Table 3-18: Regression Input Variables and Associated Model R^2

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

4.1.1 Relationship Between Mix Parameters and Compaction Methods

One of the objectives of this experiment was to assess whether or not field mixing and compaction could be adequately modeled using lab mixing and compaction techniques in the fabrication of TSRST samples. Similar materials were used in fabrication of all three types of test samples (FMFC, FMLC, LMLC), but yielded somewhat dissimilar test results with respect to fracture temperature. The fracture temperature of FMFC specimens were found to be most highly correlated with aggregate gradation (-0.62), followed by % air void content (-0.14), and finally % AC content (-0.09). Fracture temperature of FMLC specimens were not significantly correlated to any of the mix variables. The FMLC correlation coefficients for aggregate gradation, % air void content, and % AC content were -0.30, -0.35, and -0.04, respectively. The fracture temperature of LMLC specimens were most significantly correlated with age conditioning (-0.54), followed by % AC content (-0.18), % air void content (-0.08), and finally aggregate gradation (-0.03).

It is difficult to draw any solid conclusions from these results, due to the lack of long-term aging test data for the FMFC and FMLC segments of the study. Had long-term aged samples from all three fabrication methods been tested, age conditioning may have proven to be the most significant input variable for each, similar to the results of a study completed in 1994 by Jung and Vinson. (5) In Jung and Vinson's study, age conditioning was determined to be the single largest contributor to low temperature cracking followed by asphalt type. (5) The relatively few number of fine aggregate gradation samples tested

for the FMFC and FMLC portion of this experiment (9 total) also make the fracture temperature results more difficult to compare confidently. Due to the lack of data for age conditioning and aggregate type in the FMFC and FMLC portions of this study, the results of this experiment are inconclusive with respect to this objective.

4.1.2 Effects of Mix Parameters and Compaction Variables on Low Temperature Cracking

Overall, the results of this study suggest that no single mix parameter or compaction variable dominates the low temperature cracking behavior of WesTrack paving materials. Correlations between mix parameters and compaction variables considered in this study were all found to be insignificant with respect to fracture temperature as shown in Table 3-16. These results are similar to prior work done on the same topic by Jung and Vinson in 1994 with respect to the mix parameters AC content, air void content, and aggregate type, but demonstrate a weaker relationship between age conditioning and fracture temperature than that found by Jung and Vinson. (5) In Jung and Vinson's report to the Strategic Highway Research Program (SHRP), age conditioning was found to be the major contributor to fracture temperature of asphalt concrete followed by asphalt type, air void content, and the interaction between asphalt type and degree of aging. (5)

The results of the LMLC portion of this experiment more closely agreed with the report issued by Jung and Vinson than did the FMFC, FMLC, and LMLC data combined. The LMLC data showed age conditioning to be the greatest factor contributing to low temperature cracking (correlation coefficient of -0.54), but the quantity of LMLC testing

performed was not enough to substantiate solid conclusions. Potential reasons for the overall discrepancies in findings between this study and the report issued by Jung and Vinson are mix parameter variation between field mixing and lab mixing, compaction variation between lab technicians, and variation in sample preparation and testing.

4.1.3 Fracture Temperature Prediction Model

Fracture temperature prediction models constructed using multiple regression and the data generated from this study were all found to be statistically insignificant as shown in Table 3-18. The model with the maximum explained variation ($R^2 = .0869$) was a function of age conditioning, % air void content, % AC content, aggregate gradation, age conditioning * % air voids, age conditioning * % AC content, and age conditioning * aggregate gradation. Due to this lack of statistical significance, it was concluded that a reliable fracture temperature prediction model could not be produced using the data generated from this study.

4.2 Recommendations

Based on the results of this study, it is recommended that design for low temperature cracking of asphalt concrete pavements be taken into account during binder selection. No single mix parameter or compaction variable tested in this experiment was found to dominate the fracture temperature of asphalt pavement. Therefore, it is not recommended that low temperature cracking be included in a performance related specification for asphalt concrete pavement since failure modes such as permanent

deformation and fatigue cracking will override low temperature cracking in a HMA mix design.

Since it has previously been shown that age conditioning has an effect on fracture temperature of TSRST samples, additional testing of long-term aged specimens may be warranted to extend this database. Post mortem testing of WesTrack sections (i.e. FMFC) is planned and will provide additional data with respect to the effects of aging on fracture temperature.

REFERENCES

(1) The Asphalt Institute, Performance Graded Asphalt Binder Specification and Testing, Superpave Series, No. 1 (SP-1), Lexington, KY, 1997, page iii.

(2) The Asphalt Institute, Superpave Mix Design, Superpave Series, No. 2 (SP-2), Lexington, KY, 1996, pages 12, 65-88.

(3) The WesTrack Team, WesTrack Performance-Interim Findings, Reno, NV, 1997, pages 1-6.

(4) Strategic Highway Research Program, Low-Temperature Cracking: Test Selection, SHRP-A-400, Washington, DC, 1994, pages 11-26.

(5) Strategic Highway Research Program, Low-Temperature Cracking: Binder Validation, SHRP-A-399, Washington, DC, 1994, pages 47-50, 93-95.

(6) State of Nevada Department of Transportation Materials and Testing Division, Method For The Addition of Lime in Laboratory Prepared Bituminous Aggregate Samples, Test Method Nev. T343A.

(7) American Association of State Highway and Transportation Officials, Standard Test Method for Thermal Stress Restrained Specimen Tensile Strength, AASHTO Designation: TP10-93, First Edition, Washington, DC, 1993, pages 1-5.

Appendix

A

FMLC Compaction Temperature Determination

Binder	AC - 10
Temp (C)	Viscosity (cp)
110	1087
160	101

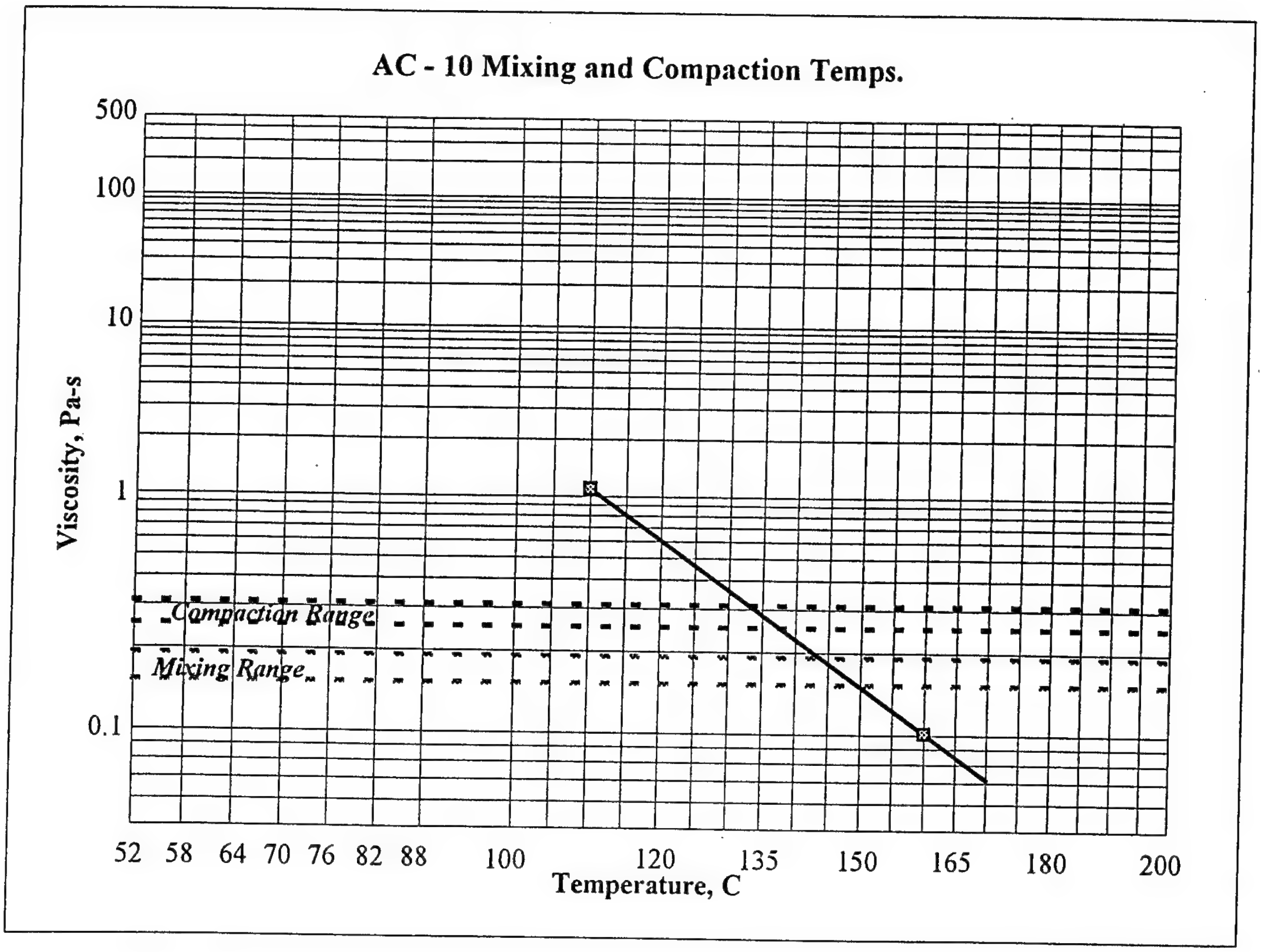
Mixing Temperature Range, C	144	-	150
Compaction Temperature Range, C	133	-	138

Specific Gravity 1.020

DSR (*Do not enter if using two RV measurements*)

Temperature, C

G*/sin δ (kPa)

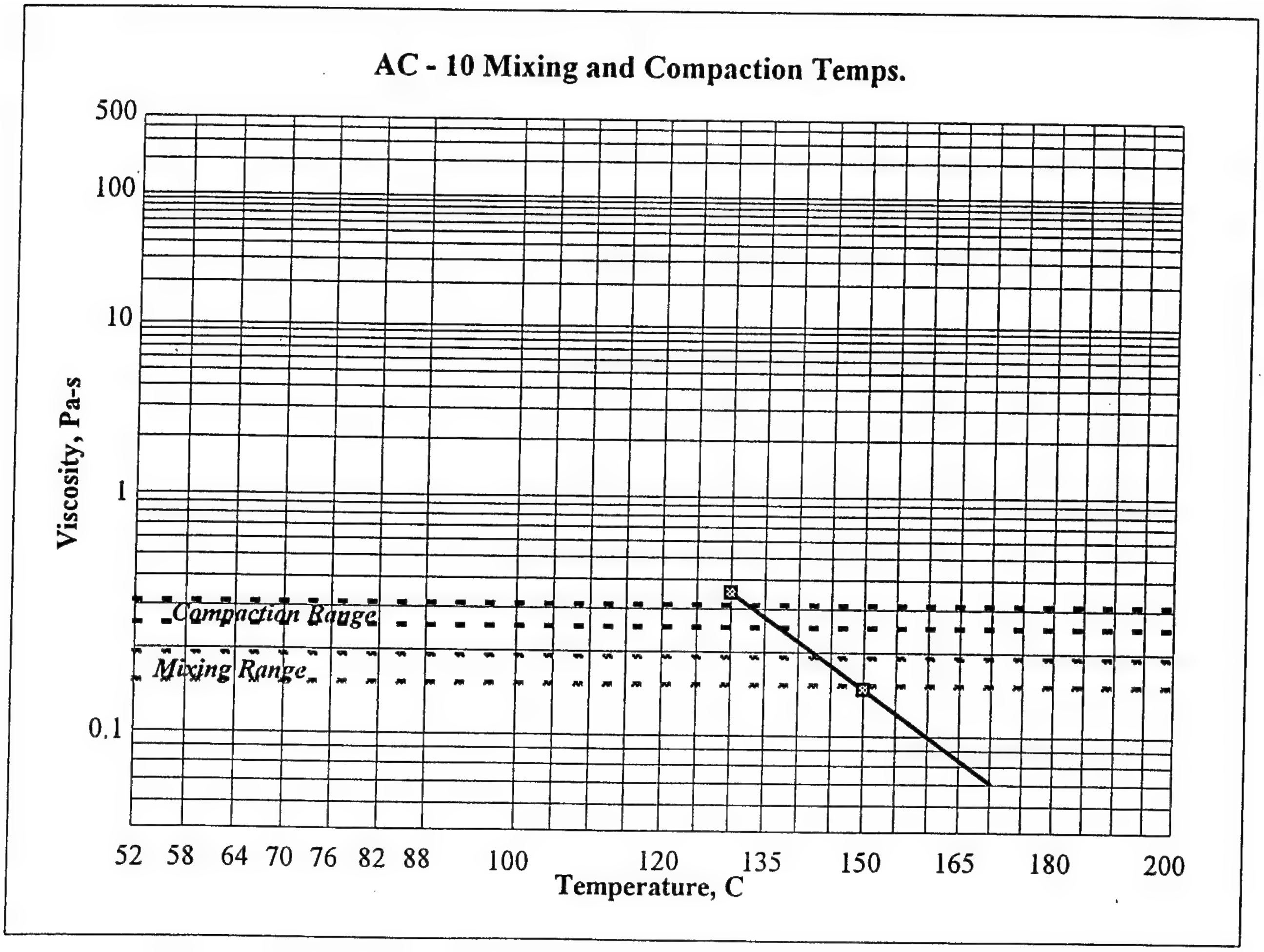


Binder	AC - 10
Temp (C)	Viscosity (cp)
130	350
150	145

Mixing Temperature Range, C 143 - 149
Compaction Temperature Range, C 133 - 137

Specific Gravity 1.020

DSR (*Do not enter if using two RV measurements*)
Temperature, C
G*/sin δ (kPa)



Appendix

B

LMLC Mixing and Compaction Data

State of Nevada
Department of Transportation
Materials and Testing Division

METHOD FOR THE ADDITION OF LIME IN LABORATORY PREPARED BITUMINOUS AGGREGATE SAMPLES

A. APPARATUS:

1. Mechanical mixer, with accessories, including mixing bowls and paddles.
2. Balance, 11 kg capacity, accurate to ± 0.1 g.
3. Small round tins, 2 3/4" (70 mm) diameter x 1 7/8" (48 mm) deep.
4. Graduated cylinder, 100 ml.
5. Pans, 11" (280 mm) x 7" (178 mm) x 1" (25 mm) deep.
6. Oven, forced air circulation, thermostatically controlled to 230°F (110°C).
7. Stopwatches
8. Plastic containers, 1 quart (1 liter) with lids.
9. Safety glasses or goggles and gloves.
10. Hydrated lime.

B. PROCEDURE:

1. Prepare 1200 gram aggregate samples as per Test Method Nev. T303.
2. Weigh out individual lime batches in the small round tins. (18 grams in each tin for 1.5% lime by dry weight of aggregate)
3. Place individual 1200 gram aggregate batch in mixing bowl.
4. Add enough moisture (water), using the 100 ml graduated cylinder, to thoroughly dampen the sample. (this will usually be 48 to 60 ml, [4% to 5%]. This amount will vary depending upon several factors including aggregate porosity, surface area, etc). 36 to 72 ml [3% to 6%]

moisture has been found to be sufficient in all cases.

5. Mix the sample with the water for 2 minutes, at which time add one small tin of hydrated lime (18 grams) and continue mixing for 3 additional minutes, for a total of 5 minutes.

6. For standard addition of lime, (no wet cure) place the "limed" mixture into a 11" (280 mm) x 7" (178 mm) x 1" (25 mm) deep pan, place in a 230°F (110°C) oven, and dry until all moisture has been removed (overnight has been found to be sufficient).

7. For aggregate mixtures that are to be marinated (48 hour wet cure) place the "limed" mixture into 1 quart (1 liter) plastic container and cover with lid for 48 hours, then proceed with step number 6 above.

PRECAUTIONS:

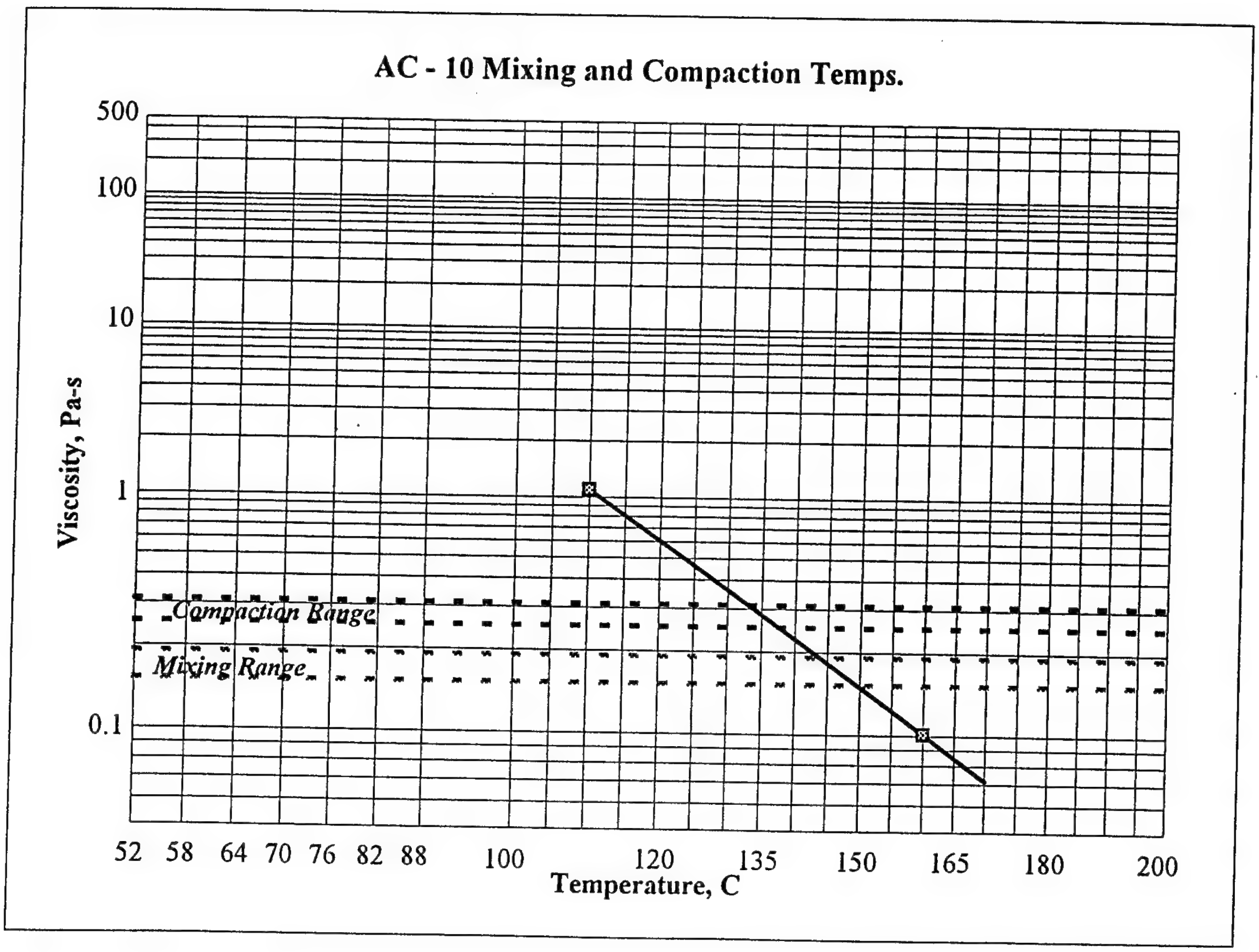
EXTRA CARE SHOULD BE TAKEN WITH THE USE OF HYDRATED LIME. ADEQUATE VENTILATION AS WELL AS THE PROPER SAFETY EQUIPMENT SHOULD BE UTILIZED WHEN WORKING WITH LIME. AVOID CONTACT WITH THE SKIN AND EYES, AND AVOID BREATHING CONTAMINATED AIR.

Binder	AC - 10
Temp (C)	Viscosity (cp)
110	1087
160	101

Mixing Temperature Range, C	144	-	150
Compaction Temperature Range, C	133	-	138

Specific Gravity 1.020

DSR (*Do not enter if using two RV measurements*)
Temperature, C
G*/sin δ (kPa)

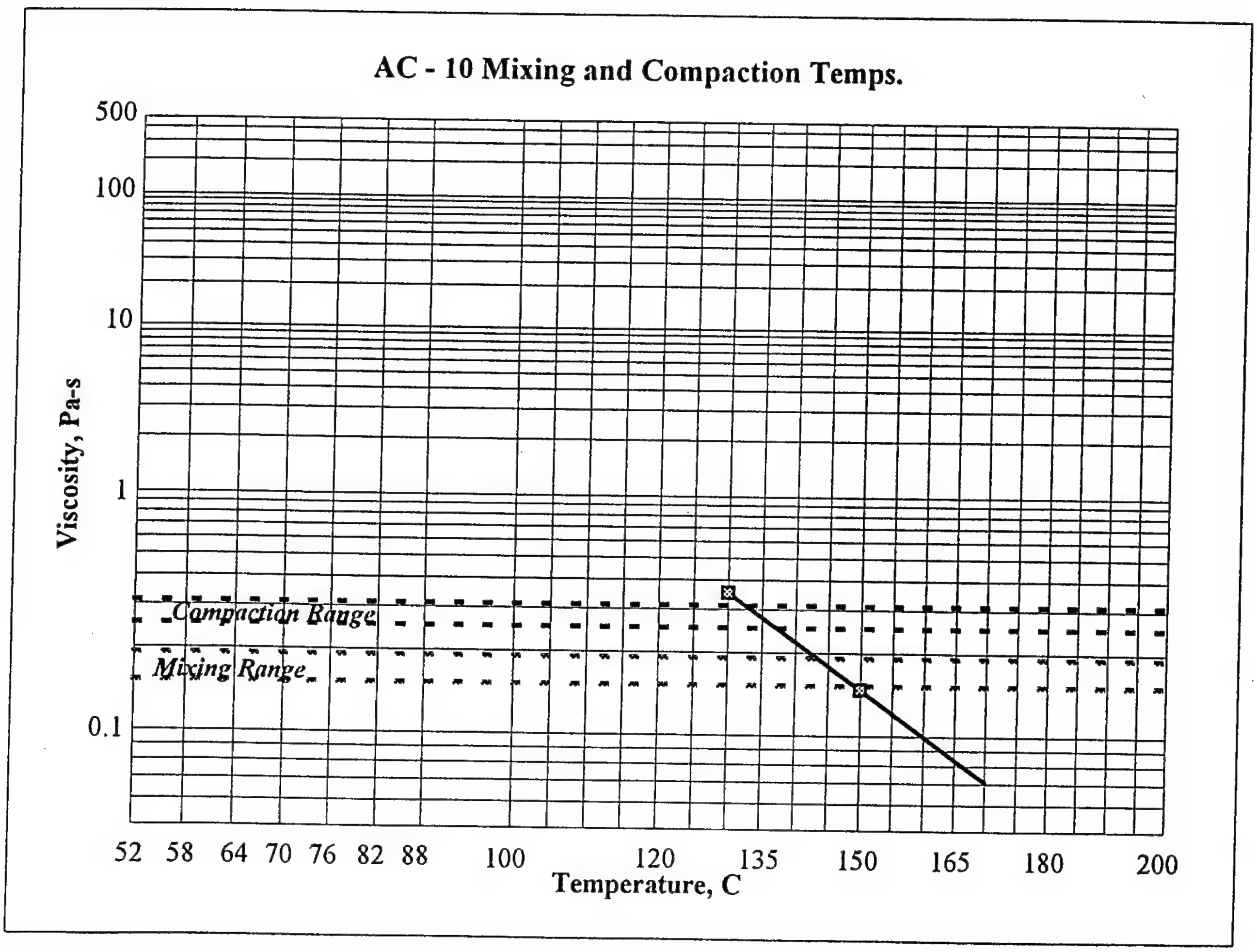


Binder	AC - 10
Temp (C)	Viscosity (cp)
130	350
150	145

Mixing Temperature Range, C	143	-	149
Compaction Temperature Range, C	133	-	137

Specific Gravity 1.020

DSR (*Do not enter if using two RV measurements*)
Temperature, C
G*/sin δ (kPa)



WesTrack TSRST LMLC
Mixing and Compaction Data

Compaction Block ID Code

WT	=	WesTrack
C/F	=	Coarse/Fine Agg Gradation
L/M/H	=	Low/Med/High AC Content
S/L	=	Short/Long Term Age
#	=	Block #

Compaction Block ID #	Pan#	Agg Mass (g)	Target AC (g)	Actual AC (g)	After °C Mix Temp.	Date 1998	Lift#	#Tamps	Pressure	Static Load	Target Air %	WesTrack Section #	Actual Air %
WTCMS1	1	5466.4	331.3	331.3	137	18-Jun	1	120	200	60,000 lb Static	8.0		5.63
	2	5467.0	331.3	330.7	136		2	150	250				5.71
WTCMS2	3	5467.0	331.3	331.5	141	18-Jun	1	150	225	60,000 lb Static	6.0		5.21
	4	5467.0	331.3	331.5	134		2	175	275			Sec 39S, smpl A	4.09
WTCMS3	1	5467.0	331.3	332.0	135	19-Jun	1			60,000 lb Static	12.0	Sec 36S, smpl A	12.96
	2	5461.0	331.3	331.2	135		2					Sec 36S, smpl B	13.00
WTCMS4	1	5461.2	331.3	331.8	137	23-Jun	1	25 / 125	100 / 150	60,000 lb Static	8.0	Sec 39S, smpl B	4.34
WTCML4	2	5464.0	331.3	331.0	135		2	25 / 175	150 / 225			Sec 39L, smpl A	4.04
WTCML5	1	5470.0	331.3	331.8	135	23-Jun	1	150	225	60,000 lb Static	6.0	Sec 39L, smpl B	4.00
WTCMS5	2	5475.0	331.3	331.2	140		2	175	275			Sec 39S, smpl C	3.58
WTCMS6	1	5467.0	331.3	331.7	135	26-Jun	1	100	125	60,000 lb Static	8.0		6.59
	2	5466.0	331.3	331.5	132		2	120	150				6.25
WTCMS7	1	5459.0	331.3	331.0	133	26-Jun	1	80	100	60,000 lb Static	8.0		6.65
	2	5465.5	331.3	330.5	134		2	100	125				5.50
WTCML8	1	5471.0	331.3	331.8	138	30-Jun	1	25 / 125	100 / 150	60,000 lb Static	4.0		4.13
	2	5469.0	331.3	332.5	234		2	25 / 175	150 / 225			Sec 39L, smpl C	3.83
WTCMS9	3	5474.0	331.3	331.8	141	30-Jun	1	75	50	40,000 lb Static	8.0	Sec 35S, smpl A	7.23
	4	5472.0	331.3	332.0	137		2	75	75			Sec 35S, smpl B	7.67
WTCMS10	1	5464.0	331.3	331.6	138	3-Jul	1	50	50	40,000 lb Static	8.0		10.02
WTCML10	2	5466.0	331.3	332.5	143		2	50	75			Sec 35L, smpl C	8.97
WTCML11	3	5413.5	331.3	331.0	139	3-Jul	1	50	50	40,000 lb Static	8.0	Sec 35L, smpl A	8.48
	4	5472.0	331.3	331.6	135		2	75	75			Sec 35L, smpl B	7.66
WTCHS12	1	5471.0	374.8	374.4	134	7-Jul	1	25 / 100	100 / 125	60,000 lb Static	4.0	Sec 25S, smpl A	4.67
	2	5471.0	374.8	374.4	138		2	25 / 125	100 / 150				5.89

Compaction Block ID #	Pan#	Agg Mass (g)	Target AC (g)	Actual AC (g)	After °C Mix Temp.	Date 1998	Lift#	#Tamps	Pressure	Static Load	Target Air %	WesTrack Section #	Actual Air %
WTCMS13	3	5461.0	331.3	332.4	138	7-Jul	1			60,000 lb Static	12.0		13.50
WTCML13	4	5471.0	331.3	332.0	135		2					Sec 36L, smpl A	12.95
WTCMS14	1	5466.0	331.3	331.4	136	13-Jul	1	50	50	40,000 lb Static	8.0		9.46
	2	5461.0	331.3	332.0	130		2	75	75			Sec 35S, smpl C	8.99
WTCML15	3	5464.0	331.3	331.8	136	13-Jul	1	Rodded 85 Times		60,000 lb Static	12.0	Sec 36L, smpl B	12.54
	4	5466.0	331.3	331.6	133		2						12.38
WTCML16	1	5464.0	331.3	332.0	138	17-Jul	1	Rodded 85 Times		60,000 lb Static	12.0	Sec 36L, smpl C	11.25
WTCMS16	2	5471.0	331.3	332.2	135		2					Sec 36S, smpl C	11.63
WTCHS17	3	5462.0	374.4	374.4	137	17-Jul	1	25 / 100	100 / 150	60,000 lb Static	4.0		2.48
	4	5474.0	374.4	374.4	134		2	25 / 150	175 / 200				2.69
WTCHS18	1	5468.0	374.4	374.4	131	21-Jul	1	25 / 100	100 / 150	60,000 lb Static	4.0	Sec 25S, smpl B	4.71
	2	5468.0	374.4	374.4	131		2	25 / 125	125 / 175				5.13
WTCLS19	3	5467.0	288.5	288.3	136	21-Jul	1	Rodded 100 Times		60,000 lb Static	12.0		13.00
	4	5467.0	288.5	288.6	135		2					Sec 26S, smpl B	12.63
WTCHL20	1	5470.0	374.4	375.0	137	23-Jul	1	25 / 100	100 / 150	60,000 lb Static	4.0		4.46
	2	5466.0	374.4	374.3	129		2	25 / 125	125 / 200			Sec 25L, smpl B	4.25
WTCLL21	3	5469.0	288.5	288.6	137	23-Jul	1	Rodded 125 Times		60,000 lb Static	12.0	Sec 26L, smpl A	12.43
	4	5470.0	288.5	289.0	136		2	Hold load 30 Sec				Sec 26L, smpl B	12.88
WTCHS22	1	5460.0	374.4	374.7	137	28-Jul	1	25 / 100	100 / 150	60,000 lb Static	4.0	Sec 25S, smpl C	5.00
WTCHL22	2	5469.0	374.4	374.2	137		2	25 / 125	125 / 200			Sec 25L, smpl C	3.91
WTCLS23	3	5463.0	288.5	288.8	135	28-Jul	1	Rodded 125 Times		60,000 lb Static	12.0		12.18
WTCLL23	4	5467.0	288.5	289.0	134		2	Hold load 30 Sec				Sec 26L, smpl C	12.26
WTFMS24	1	5466.0	312.9	313.3	128	4-Aug	1	50	50	40,000 lb Static	8.0	Sec 01S, smpl A	8.95
	2	5464.0	312.9	312.9	140		2	75	75			Sec 01S, smpl B	8.20
WTFMS25	3	5469.0	312.9	313.2	132	4-Aug	1	Rodded 85 Times		60,000 lb Static	12.0	Sec 17S, smpl A	12.67
	4	5471.0	312.9	312.7	137		2					Sec 17S, smpl B	11.88
WTFML26	1	5467.0	312.9	313.0	138	7-Aug	1	50	50	40,000 lb Static	8.0	Sec 01L, smpl A	8.01
	2	5467.0	312.9	312.8	135		2	75	100			Sec 01L, smpl B	8.18
WTFML27	3	5469.0	312.9	312.8	143	7-Aug	1	Rodded 85 Times		60,000 lb Static	12.0	Sec 17L, smpl A	11.75
	4	5466.0	312.9	312.6	140		2						10.80
WTFMS28	5	5462.0	312.9	312.6	137	20-Aug	1	50	50	40,000 lb Static	8.0	Sec 01S, smpl C	8.37
WTFML28	6	5463.0	312.9	312.8	135		2	75	100			Sec 01L, smpl C	8.33
WTFML29	7	5458.0	312.9	312.4	140	20-Aug	1	Rodded 50 Times		60,000 lb Static	12.0	Sec 17L, smpl B	12.81
WTFMS29	8	5456.0	312.9	313.0	140		2					Sec 17S, smpl C	11.85

Compaction Block ID #	Pan#	Agg Mass (g)	Target AC (g)	Actual AC (g)	After °C Mix Temp.	Date 1998	Lift#	#Tamps	Pressure	Static Load	Target Air %	WesTrack Section #	Actual Air %
WTFML30	1	5473.0	312.9	312.8	137	25-Aug	1	Rodded 50 Times		60,000 lb Static	12.0		11.55
	2	5470.0	312.9	313.1	135		2					Sec 17L, smpl C	12.60
WTFMS31	3	5473.0	312.9	313.1	133	25-Aug	1	25 / 125	100 / 150	60,000 lb Static	4.0	Sec 04S, smpl A	4.98
	4	5469.0	312.9	313.1	133		2	25 / 175	150 / 225				5.36
WTFHS32	5	5458.0	356.1	355.9	137	25-Aug	1	25 / 100	100 / 150	60,000 lb Static	4.0	Sec 18S, smpl A	4.04
	6	5478.0	356.1	356.2	139		2	25 / 125	125 / 200			Sec 18S, smpl B	4.80
WTFLS33	7	5465.0	270.3	270.6	135	25-Aug	1	Rodded 125 Times		60,000 lb Static	12.0	Sec 03S, smpl A	12.63
	8	5467.0	270.3	270.3	136		2	Hold load 30 Sec				Sec 03S, smpl B	11.75
WTFMS34	1	5464.0	312.9	312.7	132	8-Sep	1	50 / 125	125 / 150	60,000 lb Static	4.0	Sec 04S, smpl B	4.98
	2	5463.0	312.9	312.9	134		2	50 / 175	150 / 225				5.69
WTFHL35	3	5472.0	356.1	355.9	134	8-Sep	1	25 / 100	100 / 150	60,000 lb Static	4.0	Sec 18L, smpl A	4.67
	4	5467.0	356.1	356.3	136		2	25 / 125	125 / 200			Sec 18L, smpl B	4.84
WTFLL36	5	5466.0	270.3	270.6	135	8-Sep	1	Rodded 125 Times		60,000 lb Static	12.0	Sec 03L, smpl A	13.00
	6	5464.0	270.3	270.5	138		2	Hold load 30 Sec				Sec 03L, smpl B	12.55
WTFLS37	7	5467.0	270.3	270.3	129	8-Sep	1	Rodded 125 Times		60,000 lb Static	12.0	Sec 03S, smpl C	12.80
WTFLL37	8	5460.0	270.3	270.5	132		2	Hold load 30 Sec				Sec 03L, smpl C	12.76
WTFML38	1	5470.0	312.9	312.6	130	14-Sep	1	25 / 150	100 / 150	60,000 lb Static	4.0	Sec 04L, smpl A	4.98
	2	5469.0	312.9	312.7	131		2	25 / 225	150 / 175				5.99
WTFML39	3	5472.0	312.9	313.1	136	14-Sep	1	25 / 150	100 / 150	60,000 lb Static	4.0		6.40
WTFMS39	4	5465.0	312.9	312.8	136		2	25 / 225	150 / 175				6.28
WTFHL40	5	5472.0	356.1	356.2	139	14-Sep	1	25 / 100	100 / 150	60,000 lb Static	4.0	Sec 18L, smpl C	4.00
WTFHS40	6	5460.0	356.1	356.0	136		2	25 / 125	125 / 200			Sec 18S, smpl C	4.93
WTCHL41	7	5470.0	374.4	374.6	135	14-Sep	1	25 / 100	100 / 150	60,000 lb Static	4.0		3.49
	8	5475.0	374.4	374.5	139		2	25 / 125	125 / 200			Sec 25L, smpl A	3.91
WTFML42	1	5468.0	312.9	313.3	135	18-Sep	1	25 / 150	100 / 150	60,000 lb Static	4.0	Sec 04L, smpl B	4.73
	2	5470.0	312.9	313.3	133		2	25 / 225	150 / 175				5.57
WTFML43	1	5462.0	312.9	313.3	135	23-Sep	1	50 / 125	100 / 150	60,000 lb Static	4.0	Sec 04L, smpl C	3.93
	2	5459.0	312.9	313.2	133		2	100 / 200	100 / 200				4.82
WTFMS44	3	5469.0	312.9	313.3	134	23-Sep	1	50 / 125	100 / 150	60,000 lb Static	4.0	Sec 04S, smpl C	4.27
	4	5472.0	312.9	312.8	133		2	100 / 250	100 / 200				5.23
WTCLS45	1	5473.0	288.5	289.0	135	14-Oct	1	Rodded 125 Times		60,000 lb Static	12.0	Sec 26S, smpl A	12.88
	2	5463.0	288.5	290.6	134		2	Hold load 30 Sec				Sec 26S, smpl C	12.96

Westrack Bulk Specific Gravities and Air Void Contents

Target Air Voids: 4.0% (SSD Method only)

WesTrack Section ID #	Compaction Block ID	Dry Mass	mass in water	mass SSD	SSD Gmb	Gmm	SSD % Voids
	wtcms1-1	1495.2	837.7	1498.0	**2.264**	2.398	**5.63**
	wtcms1-2	1490.1	834.4	1493.1	**2.262**	2.398	**5.71**
	wtcms2-1	1455.9	818.8	1458.9	**2.274**	2.398	**5.21**
Sec 39S, sample A	wtcms2-2	1457.8	826.8	1460.3	**2.301**	2.398	**4.09**
Sec 39S, sample B	wtcms4-1	1514.2	856.7	1516.5	**2.295**	2.398	**4.34**
Sec 39L, sample A	wtcml4-2	1607.2	912.4	1610.5	**2.302**	2.398	**4.04**
Sec 39L, sample B	wtcml5-1	1529.9	867.9	1532.1	**2.303**	2.398	**4.00**
Sec 39S, sample C	wtcms5-2	1575.0	896.4	1577.3	**2.313**	2.398	**3.58**
	wtcml8-1	1500.2	851.0	1503.3	**2.300**	2.398	**4.13**
Sec 39L, sample C	wtcml8-2	1623.0	922.4	1626.0	**2.307**	2.398	**3.83**
Sec 25S, sample A	wtchs12-1	1576.6	884.2	1580.2	**2.265**	2.376	**4.67**
	wtchs12-2	1482.1	825.3	1488.1	**2.236**	2.376	**5.89**
	wtchs17-1	1590.6	906.3	1592.8	**2.317**	2.376	**2.48**
	wtchs17-2	1583.5	900.8	1585.6	**2.312**	2.376	**2.69**
Sec 25S, sample B	wtchs18-1	1527.6	856.2	1530.8	**2.264**	2.376	**4.71**
	wtchs18-2	1553.0	866.8	1555.8	**2.254**	2.376	**5.13**
	wtchl20-1	1528.6	857.4	1530.7	**2.270**	2.376	**4.46**
Sec 25L, sample B	wtchl20-2	1570.6	882.3	1572.8	**2.275**	2.376	**4.25**
Sec 25S, sample C	wtchs22-1	1528.5	853.6	1530.7	**2.257**	2.376	**5.00**
Sec 25L, sample C	wtchl22-2	1536.9	866.2	1539.2	**2.284**	2.376	**3.91**
	wtchl41-1	1524.3	860.6	1525.4	**2.293**	2.376	**3.49**
Sec 25L, sample A	wtchl41-2	1517.2	853.6	1518.3	**2.283**	2.376	**3.91**
Sec 04S, sample A	wtfms31-1	1492.4	837.8	1495.2	**2.270**	2.389	**4.98**
	wtfms31-2	1442.4	807.1	1445.1	**2.261**	2.389	**5.36**
Sec 18S, sample A	wtfhs32-1	1494.8	841.5	1497.4	**2.279**	2.375	**4.04**
Sec 18S, sample B	wtfhs32-2	1481.8	828.2	1483.6	**2.261**	2.375	**4.80**
Sec 04S, sample B	wtfms34-1	1483.6	832.7	1486.4	**2.270**	2.389	**4.98**
	wtfms34-2	1441.5	803.6	1443.4	**2.253**	2.389	**5.69**
Sec 18L, sample A	wtfhl35-1	1529.6	856.3	1532.0	**2.264**	2.375	**4.67**
Sec 18L, sample B	wtfhl35-2	1496.3	835.6	1497.8	**2.260**	2.375	**4.84**
Sec 04L, sample A	wtfml38-1	1507.0	845.0	1509.0	**2.270**	2.389	**4.98**
	wtfml38-2	1446.9	804.6	1448.9	**2.246**	2.389	**5.99**
	wtfml39-1	1432.8	794.4	1435.1	**2.236**	2.389	**6.40**
	wtfms39-2	1495.8	829.8	1498.1	**2.238**	2.389	**6.28**
Sec 18L, sample C	wtfhl40-1	1523.8	857.3	1525.2	**2.281**	2.375	**4.00**
Sec 18S, sample C	wtfhs40-2	1566.2	874.5	1568.1	**2.258**	2.375	**4.93**
Sec 04L, sample B	wtfml42-1	1538.5	864.7	1539.7	**2.279**	2.389	**4.73**
	wtfml42-2	1480.9	825.9	1482.4	**2.256**	2.389	**5.57**
Sec 04L, sample C	wtfml43-1	1473.7	833.1	1475.3	**2.295**	2.389	**3.93**
	wtfml43-2	1501.1	842.4	1502.6	**2.274**	2.389	**4.82**
Sec 04S, sample C	wtfms44-1	1474.1	831.5	1476.0	**2.287**	2.389	**4.27**
	wtfms44-2	1497.8	837.5	1499.1	**2.264**	2.389	**5.23**

Target Air Voids: 8.0% (Average of SSD and Parafilm methods)

WesTrack Section ID	Compaction Block ID	Dry Mass	parafilm method mass in water	parafilm method mass w/ parafilm	SSD method mass in water	SSD method mass SSD	parafilm Gmb	SSD Gmb	Gmm	parafilm % Voids	SSD % Voids	Average % Voids
	wtcms6-1	1456.9	803.0	1464.0	813.1	1460.1	2.231	**2.252**	2.398	6.98	6.10	**6.59**
	wtcms6-2	1554.9	858.9	1563.8	871.5	1559.3	2.237	**2.261**	2.398	6.70	5.73	**6.25**
	wtcms7-1	1548.9	852.5	1557.5	865.0	1552.6	2.227	**2.253**	2.398	7.12	6.06	**6.65**
	wtcms7-2	1503.0	835.9	1509.9	846.9	1506.5	2.256	**2.279**	2.398	5.94	4.98	**5.50**
Sec 35S, sample A	wtcms9-1	1472.1	808.1	1478.6	819.1	1478.7	2.219	**2.232**	2.398	7.45	6.93	**7.23**
Sec 35S, sample B	wtcms9-2	1549.0	847.0	1554.4	856.5	1553.7	2.208	**2.222**	2.398	7.90	7.35	**7.67**
	wtcms10-1	1403.6	750.3	1408.4	770.2	1417.9	2.150	**2.167**	2.398	10.33	9.63	**10.02**
Sec 35L, sample C	wtcml10-2	1547.7	836.6	1556.5	854.9	1560.7	2.179	**2.193**	2.398	9.11	8.56	**8.97**
Sec 35L, sample A	wtcml11-1	1493.2	810.3	1498.2	823.5	1501.5	2.188	**2.202**	2.398	8.74	8.16	**8.48**
Sec 35L, sample B	wtcml11-2	1484.9	811.9	1490.2	824.3	1492.5	2.208	**2.222**	2.398	7.91	7.33	**7.66**
	wtcms14-1	1393.7	749.8	1397.8	767.0	1406.8	2.166	**2.178**	2.398	9.67	9.16	**9.46**
Sec 35S, sample C	wtcms14-2	1406.6	759.5	1411.3	776.7	1418.6	2.175	**2.191**	2.398	9.28	8.62	**8.99**
Sec 01S, sample A	wtfms24-1	1493.7	806.8	1495.8	812.6	1498.1	2.175	**2.179**	2.391	9.02	8.87	**8.95**
Sec 01S, sample B	wtfms24-2	1510.8	821.9	1512.6	827.8	1516.8	2.194	**2.193**	2.391	8.25	8.29	**8.20**
Sec 01L, sample A	wtfml26-1	1521.3	829.1	1523.6	833.5	1524.9	2.199	**2.200**	2.391	8.05	7.97	**8.01**
Sec 01L, sample B	wtfml26-2	1473.5	801.8	1476.2	806.3	1477.2	2.195	**2.196**	2.391	8.21	8.14	**8.18**
Sec 01S, sample C	wtfms28-1	1452.0	788.0	1454.6	794.9	1458.0	2.188	**2.190**	2.389	8.43	8.34	**8.37**
SEc 01L, sample C	wtfml28-2	1495.4	812.0	1498.1	816.5	1499.1	2.189	**2.191**	2.389	8.37	8.30	**8.33**

Westrack Bulk Specific Gravities and Air Void Contents							
Target Air Voids: 12.0% (parafilm only)							
WesTrack Section ID	**Compaction Block ID**	**Dry Mass**	**mass in water**	**mass w/ parafilm**	**Gmb**	**Gmm**	**% Voids**
Sec 36S, sample A	wtcms3-1	1420.1	739.3	1427.0	**2.088**	2.398	**12.96**
Sec 36S, sample B	wtcms3-2	1407.1	732.3	1411.3	**2.087**	2.398	**13.00**
	wtcms13-1	1357.8	702.7	1363.4	**2.075**	2.398	**13.50**
Sec 36L, sample A	wtcml13-2	1366.2	711.2	1370.8	**2.087**	2.398	**12.95**
Sec 36L, sample B	wtcml15-1	1427.5	746.6	1432.5	**2.098**	2.398	**12.54**
	wtcml15-2	1368.1	716.7	1372.3	**2.102**	2.398	**12.38**
Sec 36L, sample C	wtcms16-1	1448.4	767.7	1453.2	**2.129**	2.398	**11.25**
Sec 36S, sample C	wtcms16-2	1444.7	763.6	1449.2	**2.123**	2.398	**11.63**
	wtcls19-1	1454.9	764.0	1459.1	**2.107**	2.422	**13.00**
Sec 26S, sample B	wtcls19-2	1424.6	750.9	1428.9	**2.116**	2.422	**12.63**
Sec 26L, sample A	wtcll21-1	1469.8	776.2	1475.5	**2.121**	2.422	**12.43**
Sec 26L, sample B	wtcll21-2	1385.9	728.3	1392.2	**2.110**	2.422	**12.88**
	wtcls23-1	1403.4	743.3	1407.0	**2.127**	2.422	**12.18**
Sec 26L, sample C	wtcll23-2	1532.1	810.9	1534.8	**2.125**	2.422	**12.26**
Sec 26S, sample A	wtcls45-1	1410.4	741.4	1414.2	**2.110**	2.422	**12.88**
Sec 26S, sample C	wtcls45-2	1382.8	726.4	1386.8	**2.108**	2.422	**12.96**
Sec 17S, sample A	wtfms25-1	1387.2	722.0	1392.2	**2.087**	2.391	**12.67**
Sec 17S, sample B	wtfms25-2	1412.6	741.5	1417.6	**2.107**	2.391	**11.88**
Sec 17L, sample A	wtfml27-1	1381.4	726.3	1383.7	**2.110**	2.391	**11.75**
	wtfml27-2	1515.1	804.4	1517.7	**2.133**	2.391	**10.80**
Sec 17L, sample B	wtfml29-1	1490.8	774.9	1493.0	**2.083**	2.389	**12.81**
Sec 17S, sample C	wtfms29-2	1438.6	755.3	1441.3	**2.106**	2.389	**11.85**
	wtfml30-1	1359.6	716.2	1359.5	**2.113**	2.389	**11.55**
Sec 17L, sample C	wtfml30-2	1361.2	708.8	1364.5	**2.088**	2.389	**12.60**
Sec 03S, sample A	wtfls 33-1	1392.1	727.7	1395.1	**2.096**	2.399	**12.63**
Sec 03S, sample B	wtfls33-2	1355.7	714.9	1358.3	**2.117**	2.399	**11.75**
Sec 03L, sample A	wtfll36-1	1393.3	725.5	1396.1	**2.087**	2.399	**13.00**
Sec 03L, sample B	wtfll36-2	1344.7	703.3	1348.0	**2.098**	2.399	**12.55**
Sec 03S, sample C	wtfls37-1	1368.6	714.1	1372.3	**2.092**	2.399	**12.80**
Sec 03L, sample C	wtfll37-2	1394.7	728.0	1397.7	**2.093**	2.399	**12.76**

Westrack Rice Maximum Specific Gravities: Coarse Gradation						
Sample ID	Percent Asphalt	Dry Mass (grams)	Sample+ pyc+H2O	Pycnometer +H2O	Gmm	Date
Med AC #1	5.7	2101.0	7427.4	6202.2	2.399	6/22/98
Med AC #2	5.7	2141.5	7450.2	6202.2	2.397	6/22/98
Med AC avg	5.7				**2.398**	
High AC	6.4	2120.1	7431.0	6203.3	**2.376**	7/14/98
Low AC	5.0	2111.7	7443.0	6203.3	**2.422**	7/14/98

Westrack Rice Maximum Specific Gravities: Fine Gradation						
Sample ID	Percent Asphalt	Dry Mass (grams)	Sample+ pyc+H2O	Pycnometer +H2O	Gmm	Date
Med AC #1	5.4	2000.0	7364.0	6202.8	2.384	8/20/98
Med AC #2	5.4	2000.2	7361.0	6202.8	2.376	8/20/98
Med AC #3	5.4	1705.4	7199.0	6202.8	2.405	8/20/98
Med AC avg					**2.389**	
Med AC #1	5.4	2000	7364.8	6203.2	2.385	8/20/98
Med AC #2	5.4	2002	7369.6	6203.1	2.396	8/20/98
Med AC avg					**2.391**	
High AC	6.1	1988.6	7354.4	6203	**2.375**	9/3/98
Low AC #1	4.7	2009.6	7379	6203	2.411	9/3/98
Low AC #2	4.7	1968.8	7346.6	6203	2.386	9/3/98
Low AC avg					**2.399**	

Appendix

C

TSRST Detailed Procedures

Standard Test Method for
Thermal Stress Restrained Specimen
Tensile Strength

AASHTO Designation TP10-93[1]

1. Scope

1.1 This method determines the tensile strength and temperature at fracture of field or laboratory compacted bituminous mixtures by measuring the tensile load in a specimen which is cooled at a constant rate while being restrained from contraction.

1.2 The values stated in SI units are to be regarded as the standard.

1.3 This Standard may involve hazardous materials, operations, and equipment. This Standard does not purport to address all of the safety problems associated with it's use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 AASHTO Standards

M231 Standard Specification for Standard Masses and Balances Used in the Testing of Highway Materials

PP3 Standard Practice for the Preparation of Asphalt Concrete Specimens by Means of the Rolling Wheel Compactor

2.2 ASTM Standards

D3202 Standard Practice for Preparation of Bituminous Mixture Beam Specimens by Means of California Kneading Compactor

D3665 Practice for Random Sampling of Construction Materials.

3. Summary of Test Method

3.1 A compacted bituminous mixture specimen, either beam or core of specified dimensions, is affixed at the ends to the platens of a test system and enclosed in an environmental chamber. An initial tensile load is applied to the specimen and the specimen is cooled at a given rate. Thermal contraction on the long axis of the specimen is monitored electronically and the initial length of the specimen is reestablished by automatic adjustment of the platens on an incremental basis to the original position. This process continues until tensile fracture of the specimen occurs.

4. Significance and Use

4.1 The thermal stress restrained specimen test provides data that allows the temperature vs stress relationship to be determined for bituminous mixture pavement materials. The derived information can be used in pavement design and structural analysis to reduce thermal cracking and improve life cycle performance of bituminous mixture pavements.

5. Apparatus

5.1 Test System - A closed-loop test system, as described in Annex 1, capable of cooling a bituminous mixture specimen at a constant rate while restraining the specimen from contraction and periodically measuring the tensile load and the specimen temperature from the beginning of the test to specimen failure.

5.2 Specimen Alignment Stand - A device similar to the device shown in Figure 1 for providing the concentric and perpendicular alignment of the platens and the specimen, and to secure the specimen and platens while the epoxy cures.

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[1] *This standard is based on SHRP Product 1021.*

5.3 Invar Rods - Two invar rods 6±1 mm (0.25±0.03 in.) in diameter and 300±10 mm (12±0.5 in.) in length

5.4 Specimen Platens - Two specimen platens 150±3mm (6±0.1 in.) in diameter and 50±3 mm (2±0.1 in) thick

5.5 Threaded Rods - Two threaded rods M6 x 1 (1/4-20 UNC), 450±10 mm (18±0.5 in.) in length, with 2 nuts each.

5.6 Balance - A balance meeting the requirements of M231, Class G2

5.7 Miscellaneous Apparatus - Plumb bob, spatula (for proportioning and mixing epoxy components), metal pans and gloves,

6. Materials

6.1 Epoxy - Thermoset DC-80 or equivalent.

6.2 Miscellaneous Materials - Modeling clay, duct tape, epoxy solvent, 240-grit sandpaper.

7. Hazards

7.1 Follow the safety requirements listed in the manufacturer's safety information sheet when using epoxy and/or epoxy solvents.

8. Test Specimens

8.1 Compacted Bituminous Mixture Specimens - Obtain specimens from a larger sample of asphalt concrete which has been taken from an existing pavement or prepared in the laboratory by coring or by sawing on all sides with a diamond blade. When the larger samples are taken from existing pavement, obtain them in accordance with ASTM D3665. When the larger samples are compacted in the laboratory prepare them in accordance with PP3 or ASTM D3202. Cored specimens, after coring, shall be 60±5 mm (2.5±0.19 in.) in diameter and 250±5 mm (10±0.25 in.) in length. Beam specimens, after sawing, shall be 50±5 mm (2.0±0.15 in.) square and 250±5 mm (10.0±0.25 in.) in length.

8.2 Measurement of Cores - Determine the diameter of cores by obtaining six measurements taken at approximately 30° intervals around the circumference of the core at the middle of the specimen length. Record the six measurements to the nearest 0.01 mm (0.001 in.). Average the six measurementsand record the result to the nearest 0.1 mm (0.01 in.). Use the average to determine the cross-sectional area of the core, and record the average cross-sectional area to the nearest 5 mm^2 (0.01 in^2).

8.3 Measurement of Beams - Determine the cross-sectional area of beams by measuring each width dimension of the specimen at the middle of the specimen length and at points on each side of the middle point. Record the width measurements to the nearest 0.01 mm (0.001 in.). Average the three measurements for each width dimension and record the result to the nearest 0.1 mm (0.01 in.). Multiply the average width dimensions and record the average cross-sectional area obtained to the nearest 5 mm^2 (0.01 $in.^2$).

9. Preparation of Apparatus and Specimen

9.1 Specimen Platen Preparation and Specimen Alignment - Clean the platens with epoxy solvent. Sand the platen surface with a piece of 240-grit sandpaper to completely remove any epoxy or specimen-end residue remaining from prior tests and to provide a rough surface for epoxy adhesion.

9.2 Using an ink marker, trace diametral lines across the top face of the bottom platen such that they connect the alignment holes on opposite sides of the platen. Also trace lines longitudinally along each side of the specimen such that each line divides the side by its midpoint. Lines on the specimen and platen will be used to provide concentric alignment. (Figure 2)

9.3 Screw the specimen platens into the alignment stand. Adjust the position of the platens to a length approximately 20 mm (1 in.) longer than the specimen length. Insert the threaded rods into holes on opposite sides of platens but do not tighten yet. Use the plumb bob to line up the holes between the top and bottom platens.

> Note 1 -- Alignment is critical to obtaining meaningful test results. Therefore, the alignment device aligns the platens and specimen, and supports the specimen in a level position.

9.4 Epoxy Preparation - Follow the mixing, proportioning, applying, and curing instructions supplied by the manufacturer for the epoxy being used. If Thermoset DC-80 made by Meyer Plastics, Inc., obtain 50±5 grams each of epoxy resin and epoxy hardener in a container suitable for mixing. Thoroughly mix the two epoxy components at a 1:1 ratio until a uniform color and consistency results.

9.5 Attaching Specimen to Platens - Apply a 3 to 6 mm (0.125 to 0.25 in.) thick film of epoxy over a 50±3 mm (2±0.125 in.) diameter area on both the top and bottom platens in the specimen alignment stand. Place the specimen between the platens and carefully lower the top platen so that the specimen ends, epoxy and platens are in contact.

9.6 Check the alignment of the specimen by comparing the marked lines on the sides of the specimen to the marked lines on the bottom platen. Rotate the specimen, if necessary, to achieve concentric alignment.

9.7 Equally apply the remaining epoxy to the intersecting surfaces between the specimen sides and the platen faces, being careful not to disturb the position of the specimen. Build up the epoxy approximately 20 mm (1 in.) along the sides of the specimen (relative to the platen face). (Figure 3).

> Note 2 -- The build-up of epoxy is necessary to provide adequate adhesion between the specimen and the platen such that failure occurs in the middle portion of the specimen rather than at the specimen/platen interface.

9.7 Recheck the alignment of the specimen by comparing the marked lines on the sides of the specimen to the marked lines on the bottom platen. Rotate the specimen, if necessary, to achieve concentric alignment.

10. Conditioning

10.1 Leave the specimen in the alignment stand for 4 to 24 hours in a 23±2°C environment to allow the epoxy to harden.

10.2 Specimen Pre-Cooling - After the epoxy has cured, tighten the nuts on the threaded rods with fingers only. Remove the specimen/platen assembly from the alignment stand and screw a clevis eyelet into the top platen. Hang the specimen/platen assembly from the eyelet in a 5±2°C environment for 6±0.5 hours prior to testing.

11. Preparation of Apparatus

11.1 Connect the specimen/platen assembly to the top U-joint clevis by inserting the eyelet between the clevis opening, aligning the holes, and inserting a pin through the holes. Screw another eyelet into the bottom platen and similarly connect the bottom eyelet to the bottom U-joint clevis. (Figure 4)

11.2 Attach the two clamps used to secure the linear variable differential transformers (LVDT's) to the bottom platen with nuts and screws.

11.3 Attach the thermistors to the specimen with modeling clay. Place one thermistor each at the bottom end, the center, and the top end of the specimen, each on a different side of the specimen. The thermistors are used to measure the temperature of the specimen surface.

11.4 Attach the cable of the resistance temperature device (RTD) to the middle portion of the specimen on a free side. Secure the cable with duct tape. The RTD is used in monitoring and controlling the environmental cabinet temperature.

11.5 Attach the two clamps used to secure the invar rods to the top platen with nuts and screws.

11.6 Insert the LVDT's into the bottom clamps and the invar rods into the top clamps. Make sure each rod and LVDT pair are aligned properly. Adjust the clamps to obtain proper alignment. After aligning the rod and LVDT, secure the clamps to the platens and secure the invar rod in the top clamp.

11.7 Adjust the position of the LVDT in the bottom clamp such that its voltage output is near zero. This adjustment is necessary to ensure that the LVDT operates in its linear range during the test.

11.8 Sufficiently loosen the threaded rods attached on opposite sides of the platens until all stresses generated during the test are fully transmitted through the specimen. Close and secure the environmental cabinet door, and begin the test procedure.

12. Procedure

12.1 Start the flow of liquid nitrogen to cool the environmental cabinet to 5°C. When the average surface temperature is 5 ± 1°C apply the initial tensile load to the specimen.

12.2 Apply an initial tensile load of 50 ± 5 N (10 ± 1 lbs.) to the specimen by manually turning the hand-crank on the step-motor to raise the top platen.

12.3 Start cooling the cabinet at a rate of 10 ± 1°C per hour.

12.4 Automatically record the environmental cabinet temperature, specimen temperature, elapsed time, specimen displacement and load as the test progresses.

12.5 Continue the test until the specimen fails and record the specimen temperature and load at failure and the time to failure.

13. Calculations

13.1 Calculate the fracture strength as follows:

$$\text{Fracture Stress} = P_{ult}/A$$

where: P_{ult} = ultimate tensile load at fracture in Newtons (pounds)

A = average cross-sectional area of specimen in mm^2 ($in.^2$)

13.2 Calculate the slope of the thermally induced stress curve as follows:

$$\text{Slope} = \delta S/\delta T$$

where: δS = average change in stress along the linear portion of the curve just prior to failure, in pascals (psi), (Figure 5)

δT = average change in temperature along the linear portion of the curve just prior to failure, in °C (Figure 5)

14. Report

14.1 Test Specimen Description - bitumen type, bitumen content, aggregate gradation, and air void percentage of the test specimen

14.2 Time to failure, nearest 0.1 hour

14.3 Specimen temperature at failure (average of the 3 thermistor readings), nearest 0.1°C

14.4 Average cross-sectional area of the specimen, nearest 5 mm^2 (0.01 $in.^2$) (Section 8.2)

14.5 Ultimate load at failure (maximum tensile load), nearest 5 N (1 lb_f)

14.6 Fracture strength, nearest 5 kPa (1 psi) (Section 13.1)

14.7 Slope of the thermally induced stress curve, nearest 100 Pa/°C (0.1 psi/°C) (Section 13.2)

14.8 Failure Description - location of break along specimen length, nature of break (angular, flat, broken aggregate, etc.)

15. Precision and Bias

15.1 Precision -The work necessary to determine the precision of this test has not yet been performed.

15.2 Bias - No justifiable statement can be made on the bias of this test method because there is no reference value available.

16. Keywords

ANNEX I
Mandatory Information

A1. Apparatus

A1.1 Figures A1, A2 and A3 present diagrams of a closed-loop test system which is capable of performing the required testing. As the environmental chamber is cooled by periodic injections of liquid nitrogen, the specimen contracts. A computer monitors the output of the LVDT's and when the average displacement (relative to the original specimen position) becomes greater than 0.002 mm (0.0001 in.) the computer sends a signal to the step motor and the motor applies a tensile load to the specimen until it stretches back to its original position. This process is repeated as the specimen is continually cooled. By restraining the specimen from contraction, tensile stress in the specimen increases until it exceeds the tensile strength of the specimen and the specimen fractures. Elapsed time, chamber and specimen surface temperature, displacement, and load are periodically measured and automatically recorded by the computer throughout the test.

A1.2 Minimum Requirements for the Test System

A1.2.1 Load Measurement:
Range: 0 to 22250 N (0 to 5000 lb_f) tension
Resolution: $\leq$ 45 N (10 lb_f)
Accuracy: $\pm$ 0.1% Full Scale

A1.2.2 Displacement Measurement:
Range: $\pm$ 0.5 mm
Resolution: < 1.25 μm (50 μ-in.)
Accuracy: $\pm$ 0.1% Full Scale

A1.2.3 Displacement Control:
Operating Range: 150 to 450 mm (6 to 17 in.)
Resolution: < 1.25 μm (50 μ-in.)
Accuracy: < 5 μm (200 μ-in.)

A1.2.4 Temperature Measurement:
Range: -50 to +25°C
Resolution: < 0.1°C
Accuracy: $\pm$ 0.3°C

A1.2.5 Temperature Control:
Range: -50 to +10°C
Resolution: < 0.1°C
Accuracy: $\pm$ 0.54° C

WesTrack LMLC Sample Dimensions

Sample ID	WesTrack Section #	Test Date	X Dimension (in) 1 (in)	X Dimension (in) 2 (in)	X Dimension (in) 3 (in)	Y Dimension (in) 1 (in)	Y Dimension (in) 2 (in)	Y Dimension (in) 3 (in)	X Average (in)	Y Average (in)	Area (in²)
WTCMS 2-2	Sec 39S, smpl A	01-Jul-98	1.960	1.994	2.028	1.984	1.980	1.977	1.994	1.980	3.95
WTCMS 4-1	Sec 39S, smpl B	03-Jul-98	1.961	1.970	1.986	1.998	2.046	2.093	1.972	2.046	4.03
WTCMS 5-2	Sec 39S, smpl C	03-Jul-98	2.069	2.089	2.135	1.986	2.000	2.000	2.098	1.995	4.19
WTCHS 22-1	Sec 25S, smpl C	06-Aug-98	2.033	2.032	2.040	2.046	2.040	2.040	2.035	2.042	4.16
WTCMS 3-1	Sec 36S, smpl A	07-Aug-98	2.007	2.010	2.006	2.060	2.062	2.058	2.008	2.060	4.14
WTCMS 3-2	Sec 36S, smpl B	07-Aug-98	2.060	2.062	2.060	1.987	1.975	2.000	2.061	1.987	4.10
WTCHS 12-1	Sec 25S, smpl A	07-Aug-98	2.100	2.090	2.112	2.038	2.045	2.050	2.101	2.044	4.29
WTCMS 18-1	Sec 25S, smpl B	07-Aug-98	2.059	2.062	2.063	1.988	1.990	1.993	2.061	1.990	4.10
WTCMS 14-2	Sec 35S, smpl C	10-Aug-98	1.983	1.977	1.987	1.996	1.996	2.003	1.982	1.998	3.96
WTCMS 16-2	Sec 36S, smpl C	10-Aug-98	2.033	2.025	2.015	2.067	2.049	2.061	2.024	2.059	4.17
WTCMS 9-1	Sec 35S, smpl A	11-Aug-98	1.983	1.987	1.975	2.021	2.029	2.040	1.982	2.030	4.02
WTCMS 9-2	Sec 35S, smpl B	11-Aug-98	2.089	2.080	2.077	2.049	2.073	2.014	2.082	2.045	4.26
WTCLS 19-2	Sec 26S, smpl B	11-Aug-98	2.068	2.076	2.056	1.975	1.982	1.996	2.067	1.984	4.10
WTCLS 19-1		12-Aug-98	2.049	2.050	2.060	2.073	2.052	2.048	2.053	2.058	4.22
WTCLS 23-1		12-Aug-98	2.030	2.040	2.043	1.979	1.990	1.993	2.038	1.987	4.05
WTFMS 24-1	Sec 01S, smpl A	13-Aug-98	2.079	2.078	2.076	2.029	2.027	2.027	2.078	2.028	4.21
WTFMS 24-2	Sec 01S, smpl B	20-Aug-98	2.108	2.125	2.135	1.990	1.993	2.117	2.123	2.033	4.32
WTFMS 25-1	Sec 17S, smpl A	20-Aug-98	2.009	2.017	2.015	2.041	2.034	2.029	2.014	2.035	4.10
WTFMS 25-2	Sec 17S, smpl B	20-Aug-98	1.992	1.973	1.985	1.995	1.995	2.113	1.983	2.034	4.03
WTFMS 28-1	Sec 01S, smpl C	25-Aug-98	2.100	1.998	2.000	2.022	2.036	2.037	2.033	2.032	4.13
WTFMS 29-2	Sec 17S, smpl C	25-Aug-98	2.000	2.003	1.995	2.080	2.100	2.110	1.999	2.097	4.19
WTCML 11-1	Sec 35L, smpl A	26-Aug-98	2.094	2.088	2.084	2.020	2.028	2.045	2.089	2.031	4.24
WTCML 13-2	Sec 36L, smpl A	26-Aug-98	1.970	1.990	2.014	2.078	2.026	2.009	1.991	2.038	4.06
WTCML 15-1	Sec 36L, smpl B	26-Aug-98	2.095	2.048	1.955	1.988	2.078	2.136	2.033	2.067	4.20
WTCML 11-2	Sec 35L, smpl B	27-Aug-98	2.076	2.079	2.078	2.000	1.950	1.933	2.078	1.961	4.07
WTCML 10-2	Sec 35L, smpl C	27-Aug-98	2.054	2.046	2.051	2.083	2.070	2.086	2.050	2.080	4.26
WTCLL 23-2	Sec 26L, smpl C	27-Aug-98	2.066	2.094	2.051	2.107	2.103	2.096	2.070	2.102	4.35
WTCHL 20-2	Sec 25L, smpl B	28-Aug-98	2.040	2.036	2.030	2.102	2.086	2.065	2.035	2.084	4.24
WTCHL 22-2	Sec 25L, smpl C	28-Aug-98	1.998	2.011	2.015	2.033	2.090	2.104	2.008	2.076	4.17
WTCML 4-2	Sec 39L, smpl A	31-Aug-98	2.048	2.104	2.159	2.033	2.066	2.091	2.104	2.063	4.34
WTCML 5-1	Sec 39L, smpl B	31-Aug-98	2.110	2.080	2.041	1.984	1.982	1.980	2.077	1.982	4.12
WTCLL 21-1	Sec 26L, smpl A	03-Sep-98	2.059	2.073	2.094	2.034	2.045	2.064	2.075	2.048	4.25

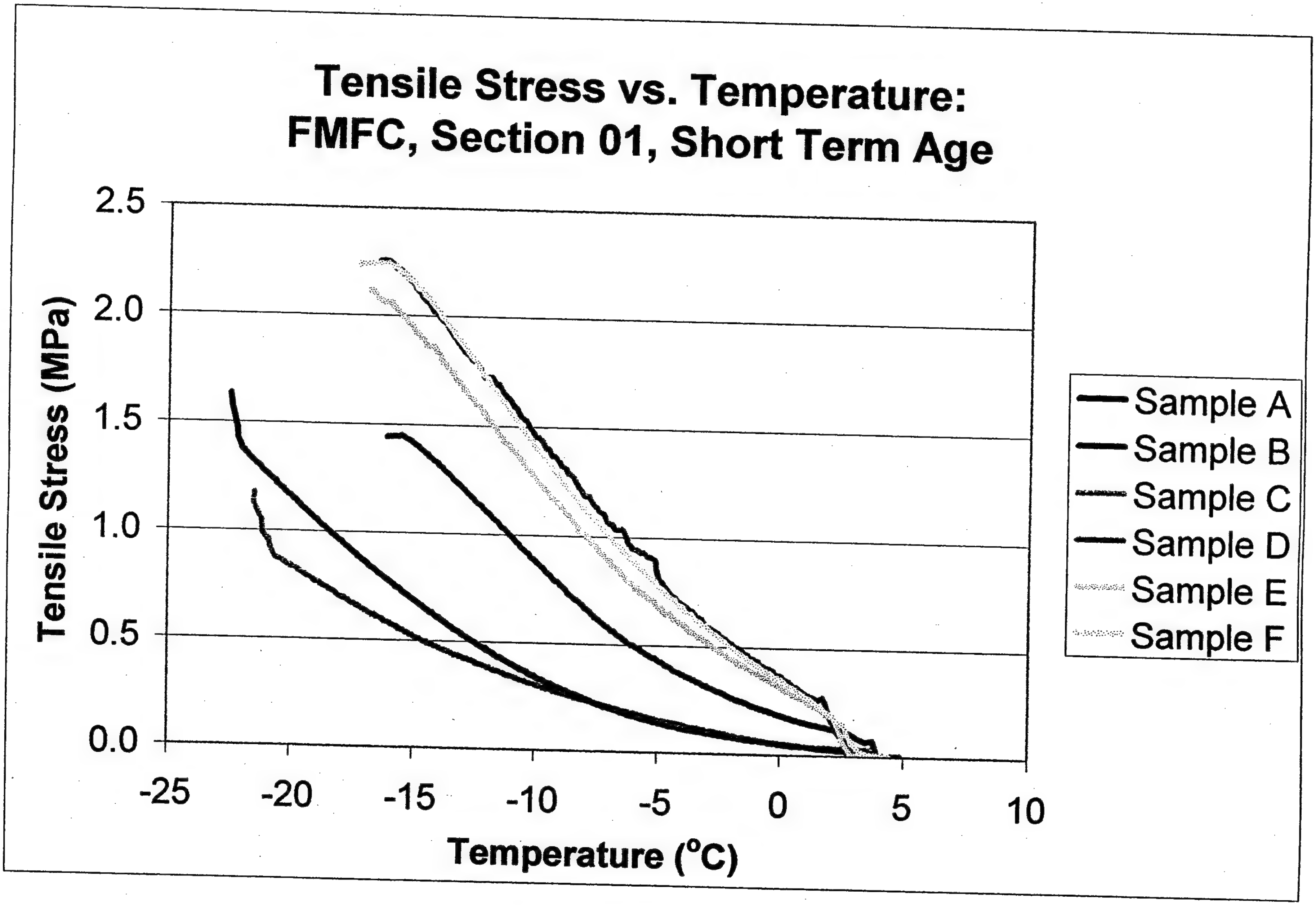
WesTrack LMLC Sample Dimensions

Sample ID	WesTrack Section #	Test Date	X Dimension (in)			Y Dimension (in)			X Average (in)	Y Average (in)	Area (in²)
			1 (in)	2 (in)	3 (in)	1 (in)	2 (in)	3 (in)			
WTCLL 21-2	Sec 26L, smpl B	03-Sep-98	1.942	1.950	1.968	2.039	2.061	2.068	1.953	2.056	4.02
WTFLS 33-1	Sec 03S, smpl A	09-Sep-98	2.082	2.058	2.037	1.988	1.997	2.018	2.059	2.001	4.12
WTFHS 32-1	Sec 18S, smpl A	09-Sep-98	1.991	2.007	2.019	2.025	2.020	2.075	2.006	2.040	4.09
WTFHS 32-2	Sec 18S, smpl B	09-Sep-98	2.045	2.055	2.064	1.979	1.990	2.018	2.055	1.996	4.10
WTFLS 33-2	Sec 03S, smpl B	13-Sep-98	1.985	2.005	2.010	2.017	1.983	1.980	2.000	1.993	3.99
WTFMS 34-1	Sec 04S, smpl B	13-Sep-98	2.045	2.052	2.062	1.990	1.988	1.993	2.053	1.990	4.09
WTFMS 31-1	Sec 04S, smpl A	13-Sep-98	2.041	2.035	2.040	2.011	2.019	2.040	2.039	2.023	4.12
WTFLS 37-1	Sec 03S, smpl C	18-Sep-98	1.990	1.997	1.988	2.015	2.015	2.015	1.992	2.015	4.01
WTCML 8-2	Sec 39L, smpl C	19-Sep-98	2.092	2.085	2.096	2.040	2.052	2.054	2.091	2.049	4.28
WTCML 16-1	Sec 36L, smpl C	19-Sep-98	2.033	2.037	2.031	2.042	2.037	2.035	2.034	2.038	4.14
WTFML 27-1	Sec 17L, smpl A	21-Sep-98	1.982	1.980	1.972	2.026	2.030	2.030	1.978	2.029	4.01
WTFHS 40-2	Sec 18S, smpl C	21-Sep-98	2.068	2.090	2.068	2.061	2.053	2.045	2.075	2.053	4.26
WTFML 28-2	Sec 01L, smpl C	22-Sep-98	2.039	2.035	2.035	2.041	2.047	2.051	2.036	2.046	4.17
WTFHL 35-2	Sec 18L, smpl B	22-Sep-98	1.997	1.986	1.975	2.010	2.018	2.050	1.986	2.026	4.02
WTFHL 35-1	Sec 18L, smpl A	22-Sep-98	2.026	2.017	2.020	2.056	2.037	2.030	2.021	2.041	4.12
WTFML 26-2	Sec 01L, smpl B	23-Sep-98	2.088	2.091	2.094	1.987	1.977	1.975	2.091	1.980	4.14
WTFML 26-1	Sec 01L, smpl A	23-Sep-98	2.058	2.052	2.058	2.054	2.050	2.041	2.056	2.048	4.21
WTFLL 37-2	Sec 03L, smpl C	23-Sep-98	2.039	2.030	2.029	2.033	2.025	2.010	2.033	2.023	4.11
WTCHL 41-2	Sec 25L, smpl A	26-Sep-98	2.072	2.065	2.060	2.043	2.028	2.010	2.066	2.027	4.19
WTFML 29-1	Sec 17L, smpl B	26-Sep-98	2.105	2.119	2.122	2.075	2.100	2.119	2.115	2.098	4.44
WTFML 38-1	Sec 04L, smpl A	26-Sep-98	2.042	2.041	2.055	2.041	2.028	2.027	2.046	2.032	4.16
WTFML 30-2	Sec 17L, smpl C	27-Sep-98	2.012	2.009	2.011	2.070	2.028	2.016	2.011	2.038	4.10
WTFHL 40-1	Sec 18L, smpl C	27-Sep-98	2.055	2.042	2.054	2.029	2.022	2.016	2.050	2.022	4.15
WTFLL 36-1	Sec 03L, smpl A	27-Sep-98	1.995	2.018	2.039	2.049	2.082	2.070	2.017	2.067	4.17
WTFLL 36-2	Sec 03L, smpl B	27-Sep-98	1.984	2.004	2.024	1.966	2.000	2.013	2.004	1.993	3.99
WTFMS 44-1	Sec 04S, smpl C	05-Oct-98	1.971	1.990	2.011	1.999	2.005	2.030	1.991	2.011	4.00
WTFML 43-1	Sec 04L, smpl C	05-Oct-98	2.023	2.023	2.026	2.011	1.985	1.975	2.024	1.990	4.03
WTFML 42-1	Sec 04L, smpl B	05-Oct-98	2.046	2.055	2.058	2.035	2.025	2.008	2.053	2.023	4.15
WTCLS 45-1	Sec 26S, smpl A	20-Oct-98	2.054	2.047	2.042	2.036	2.032	2.028	2.048	2.032	4.16
WTCLS 45-2	Sec 26S, smpl C	20-Oct-98	1.968	1.990	2.015	2.038	2.022	2.029	1.991	2.030	4.04

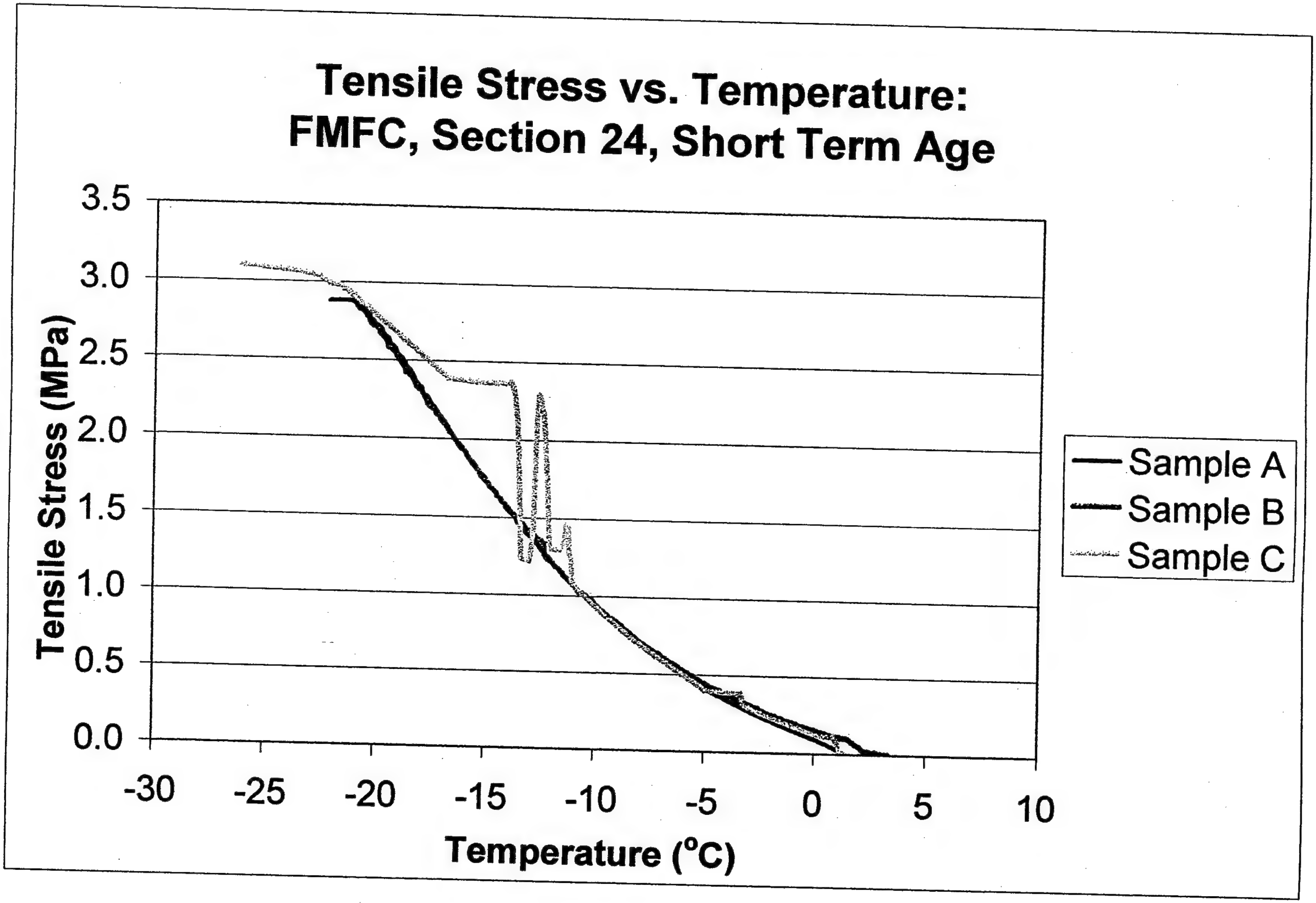
Appendix

D

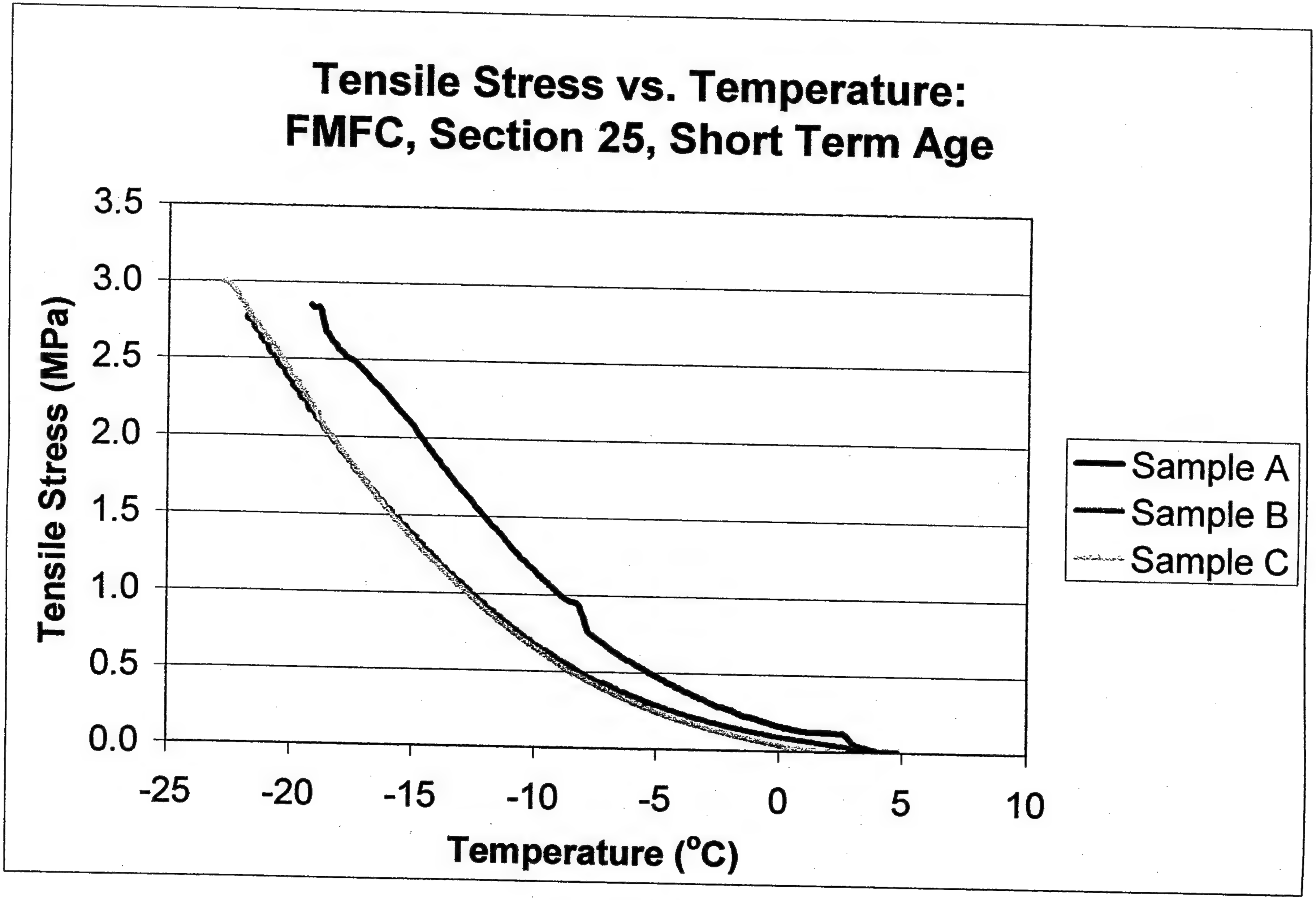
Individual FMFC TSRST Sample Data


Tensile Stress vs. Temperature:
FMFC, Section 01, Short Term Age
Tensile Stress (MPa)
2.5
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
5
10
Temperature (°C)
Sample A
Sample B
Sample C
Sample D
Sample E
Sample F

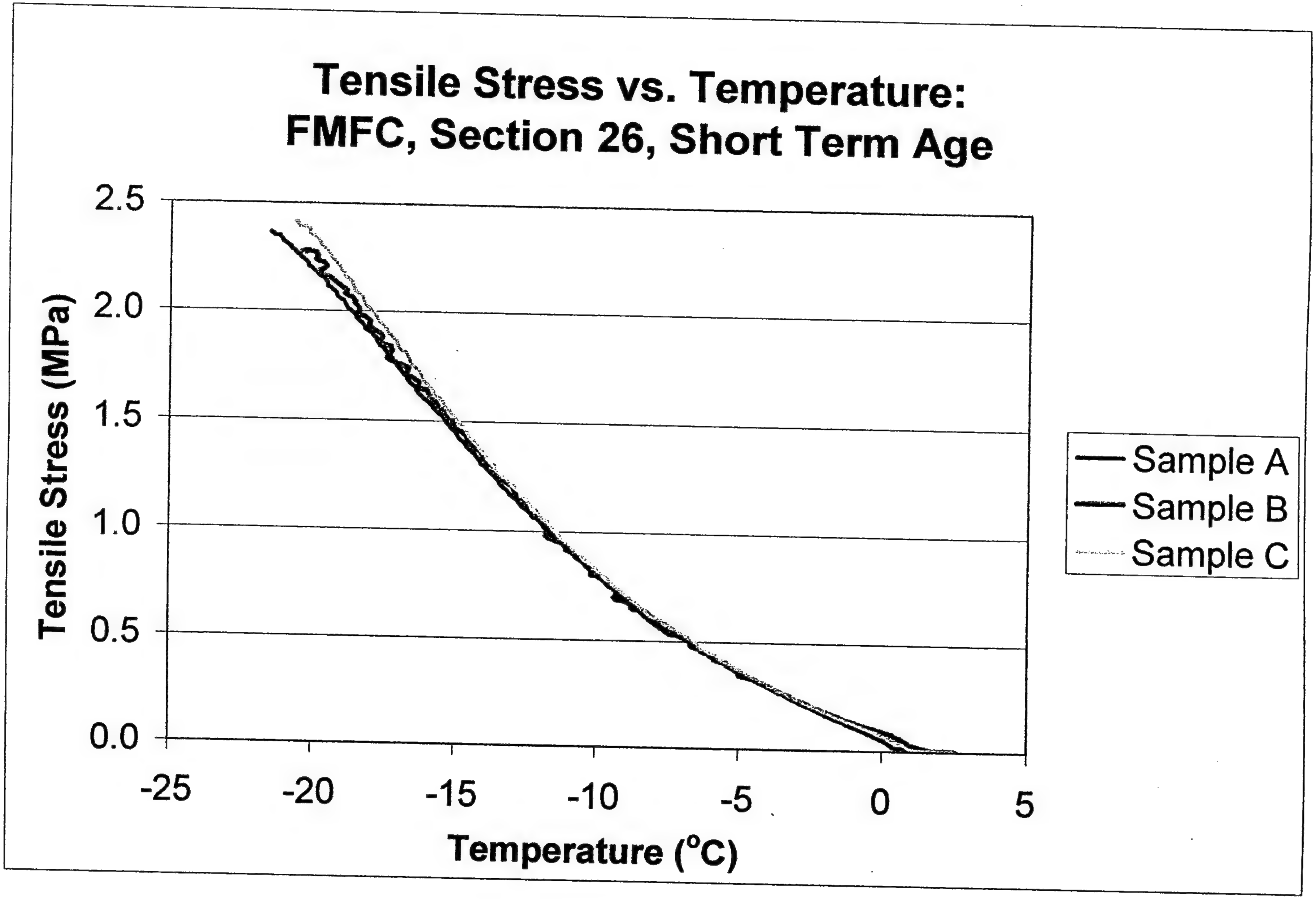
Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(^{o}C)	(^{o}F)
FMFC 01	A	8.3	1.63	237	-22.5	-8.5
	B	10.4	1.44	209	-16.1	3.0
	C	10.9	1.18	171	-21.5	-6.7
	D	10.9	2.25	326	-16.5	2.3
	E	6.8	2.11	306	-16.9	1.6
	F	7.3	2.23	324	-17.3	0.9
	Mean	9.1	1.81	262	-18.5	-1.2
	Min	6.8	1.18	171	-16.1	3.0
	Max	10.9	2.25	326	-22.5	-8.5


Tensile Stress vs. Temperature:
FMFC, Section 24, Short Term Age
Tensile Stress (MPa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30
-25
-20
-15
-10
-5
0
5
10
Temperature (°C)
Sample A
Sample B
Sample C

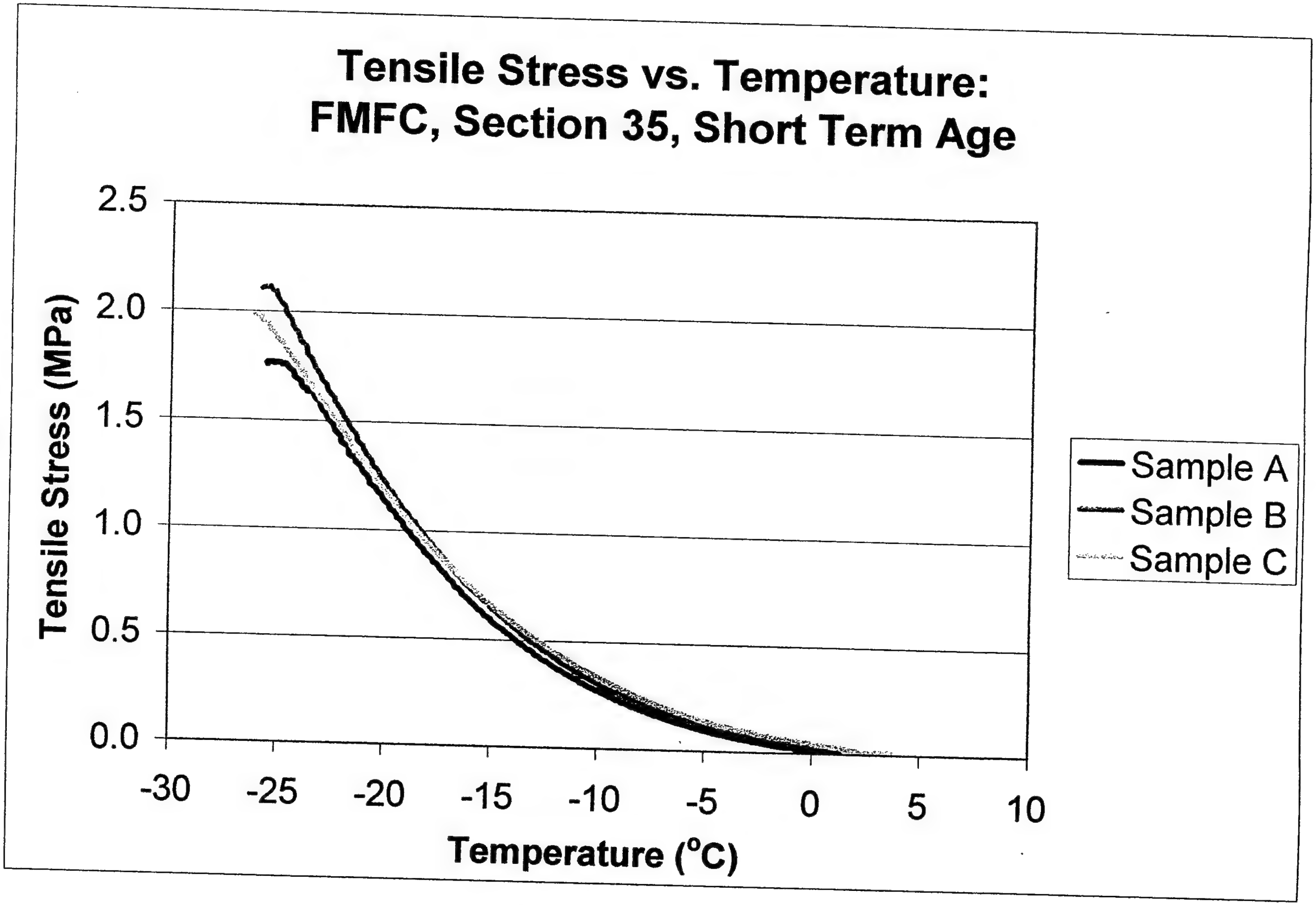
Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMFC 24	A	4.5	2.88	418	-22.1	-7.8
	B	5.0	2.96	429	-21.5	-6.7
	C	3.9	3.10	450	-26.1	-15.0
	Mean	4.5	2.98	432	-23.2	-9.8
	Min	3.9	2.88	418	-21.5	-6.7
	Max	5.0	3.10	450	-26.1	-15.0


Tensile Stress vs. Temperature:
FMFC, Section 25, Short Term Age
Tensile Stress (MPa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
5
10
Temperature (°C)
Sample A
Sample B
Sample C

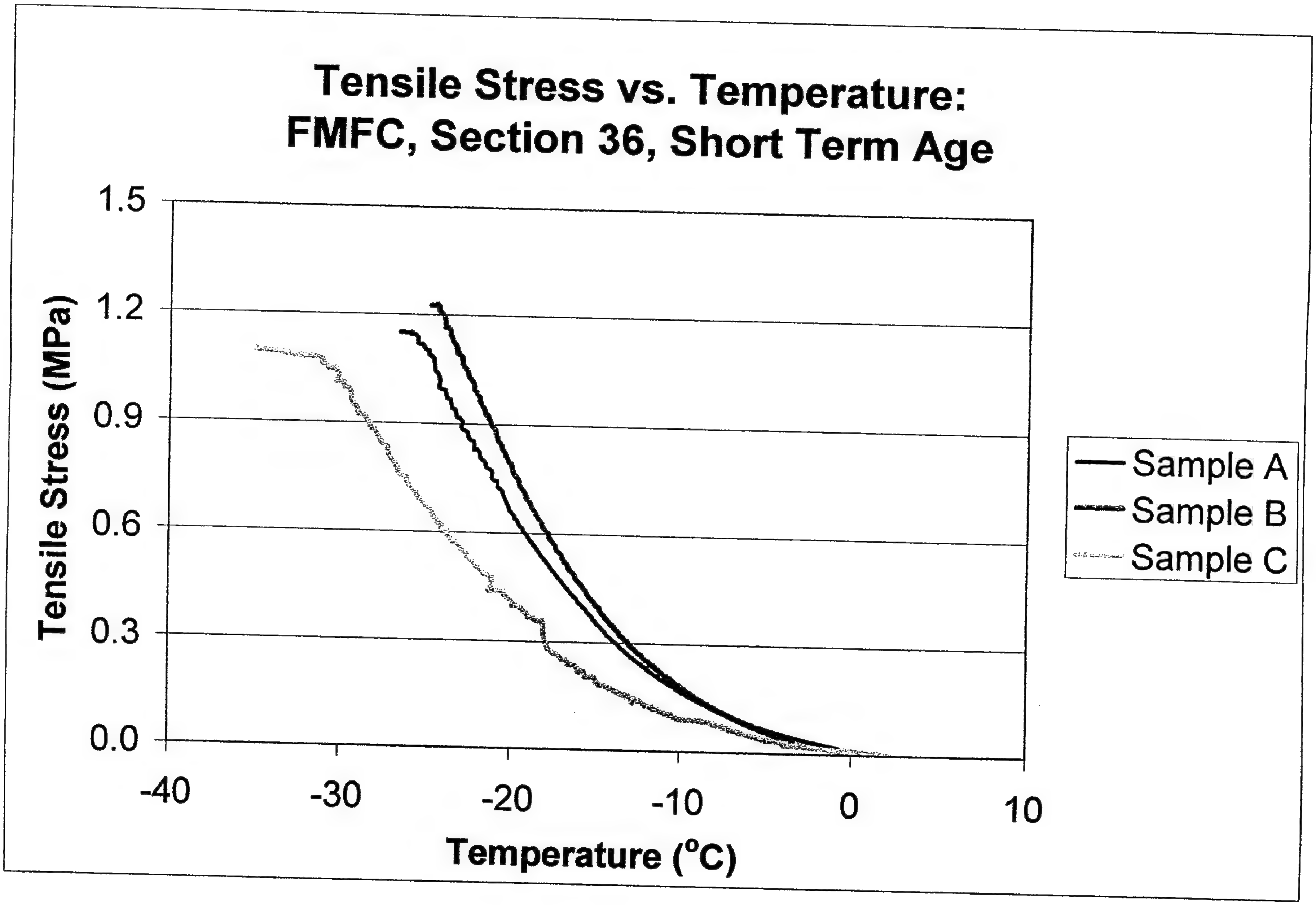
Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMFC 25	A	2.5	2.86	414	-19.2	-2.6
	B	2.3	2.78	402	-21.8	-7.2
	D	3.1	3.00	435	-22.8	-9.0
	Mean	2.6	2.88	417	-21.3	-6.3
	Min	2.3	2.78	402	-19.2	-2.6
	Max	3.1	3.00	435	-22.8	-9.0


Tensile Stress vs. Temperature:
FMFC, Section 26, Short Term Age
Tensile Stress (MPa)
2.5
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
5
Temperature (°C)
Sample A
Sample B
Sample C

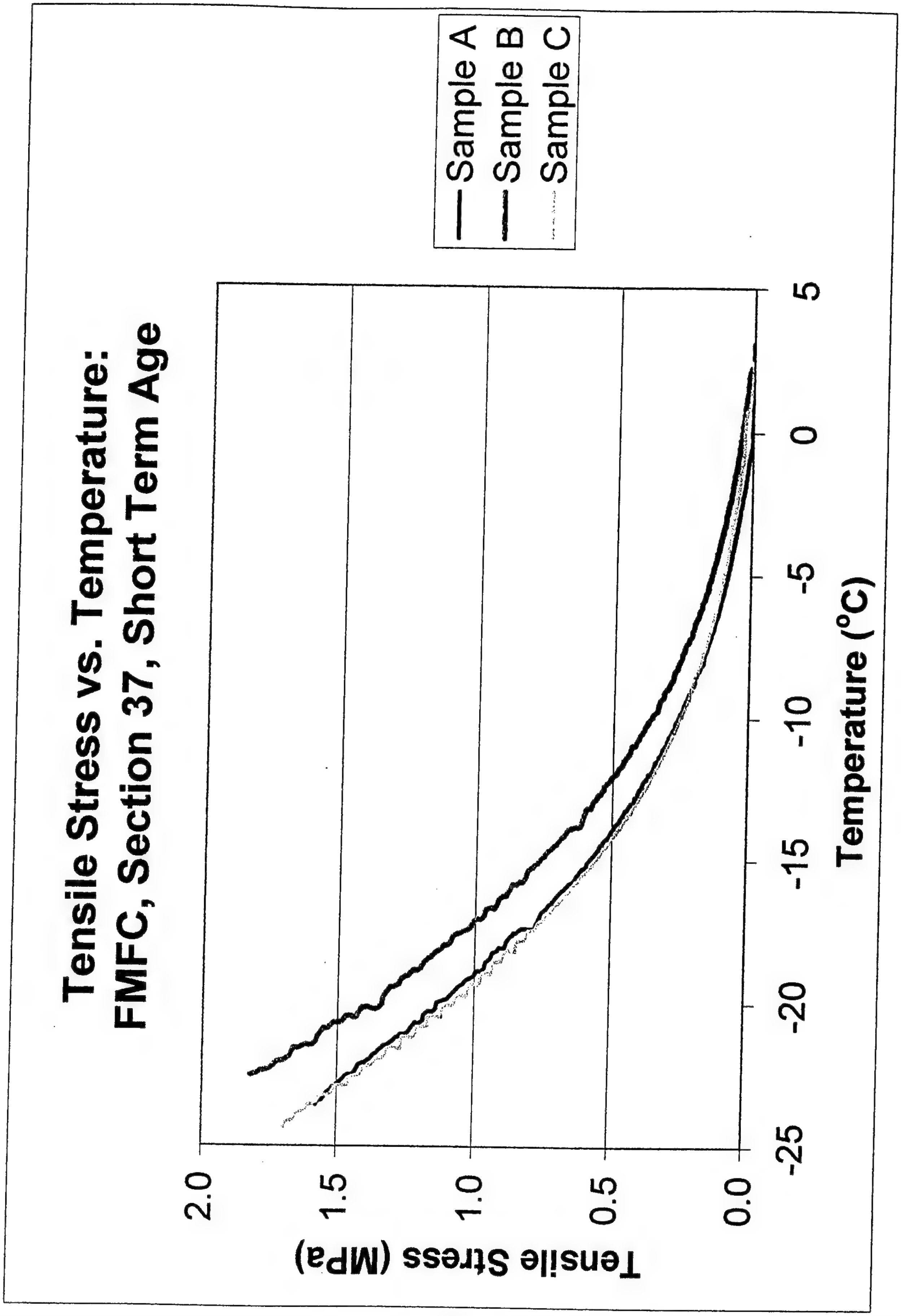
Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(^{o}C)	(^{o}F)
FMFC 26	A	8.2	2.37	343	-21.5	-6.7
	B	8.4	2.28	330	-20.3	-4.5
	C	8.6	2.41	350	-20.7	-5.3
	Mean	8.4	2.35	341	-20.8	-5.5
	Min	8.2	2.28	330	-20.3	-4.5
	Max	8.6	2.41	350	-21.5	-6.7


Tensile Stress vs. Temperature:
FMFC, Section 35, Short Term Age
Tensile Stress (MPa)
2.5
2.0
1.5
1.0
0.5
0.0
-30
-25
-20
-15
-10
-5
0
5
10
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(^oC)	(^oF)
FMFC 35	A	8.1	1.76	255	-25.5	-13.9
	B	8.1	2.11	306	-25.8	-14.4
	C	7.8	1.99	288	-26.1	-15.0
	Mean	8.0	1.95	283	-25.8	-14.5
	Min	7.8	1.76	255	-25.5	-13.9
	Max	8.1	2.11	306	-26.1	-15.0

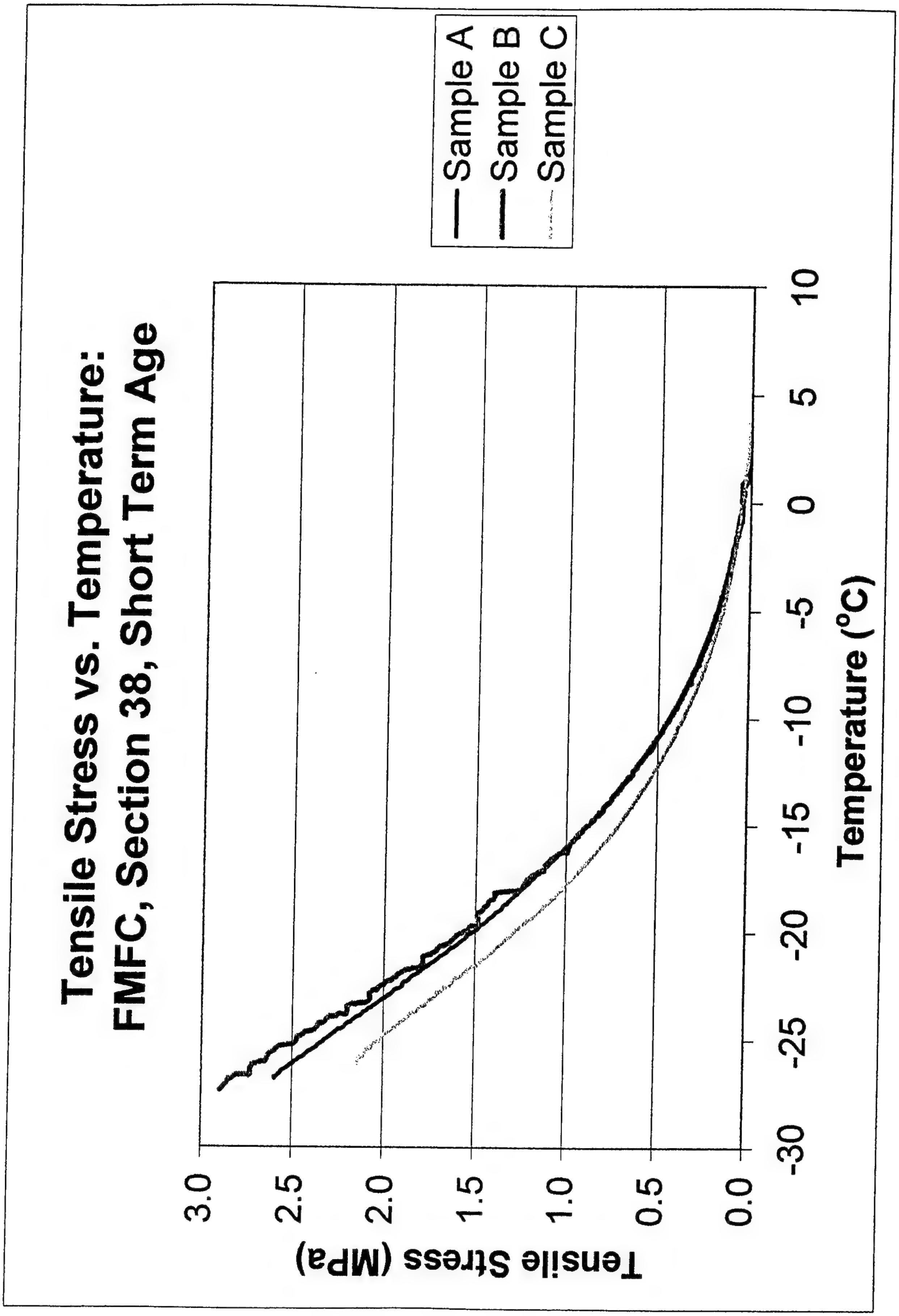

Tensile Stress vs. Temperature:
FMFC, Section 36, Short Term Age
Tensile Stress (MPa)
1.5
1.2
0.9
0.6
0.3
0.0
-40
-30
-20
-10
0
10
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMFC 36	A	12.4	1.15	167	-26.5	-15.7
	B	12.5	1.23	178	-24.8	-12.6
	C	12.5	1.10	159	-35.0	-31.0
	Mean	12.4	1.16	168	-28.7	-19.7
	Min	12.4	1.10	159	-24.8	-12.6
	Max	12.5	1.23	178	-35.0	-31.0



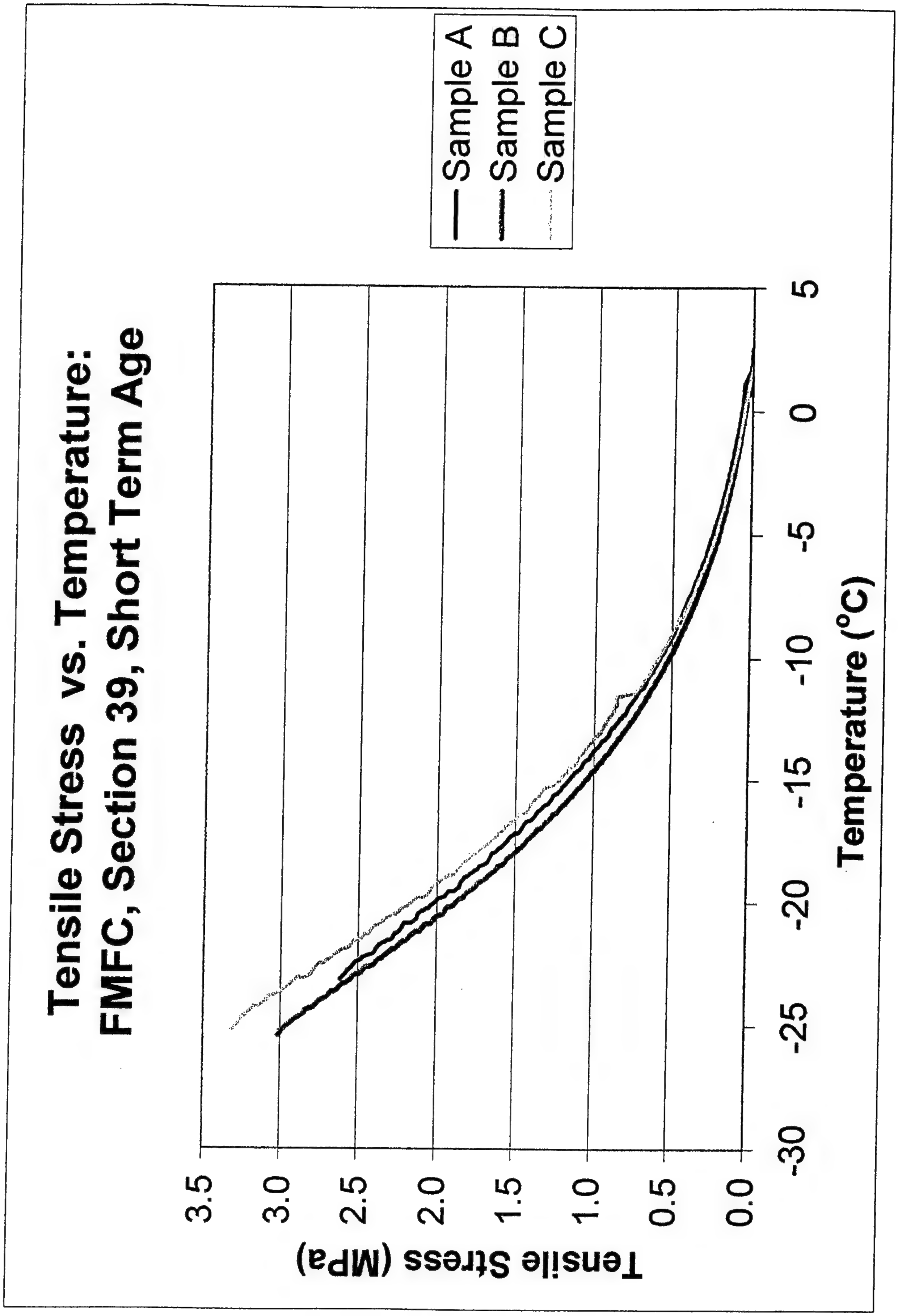
Tensile Stress vs. Temperature:
FMFC, Section 37, Short Term Age
Tensile Stress (MPa)
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
5
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMFC 37	A	9.5	1.58	229	-23.6	-10.4
	B	8.3	2.14	310	-25.1	-13.2
	C	9.6	1.70	246	-24.4	-11.9
	Mean	9.1	1.80	262	-24.3	-11.8
	Min	8.3	1.58	229	-23.6	-10.4
	Max	9.6	2.14	310	-25.1	-13.2



Tensile Stress vs. Temperature:
FMFC, Section 38, Short Term Age
Tensile Stress (MPa)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30
-25
-20
-15
-10
-5
0
5
10
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMFC 38	A	6.9	2.59	376	-26.8	-16.3
	B	6.6	2.90	420	-27.4	-17.2
	C	8.1	2.14	311	-26.1	-15.0
	Mean	7.2	2.54	369	-26.8	-16.2
	Min	6.6	2.14	311	-26.1	-15.0
	Max	8.1	2.90	420	-27.4	-17.2



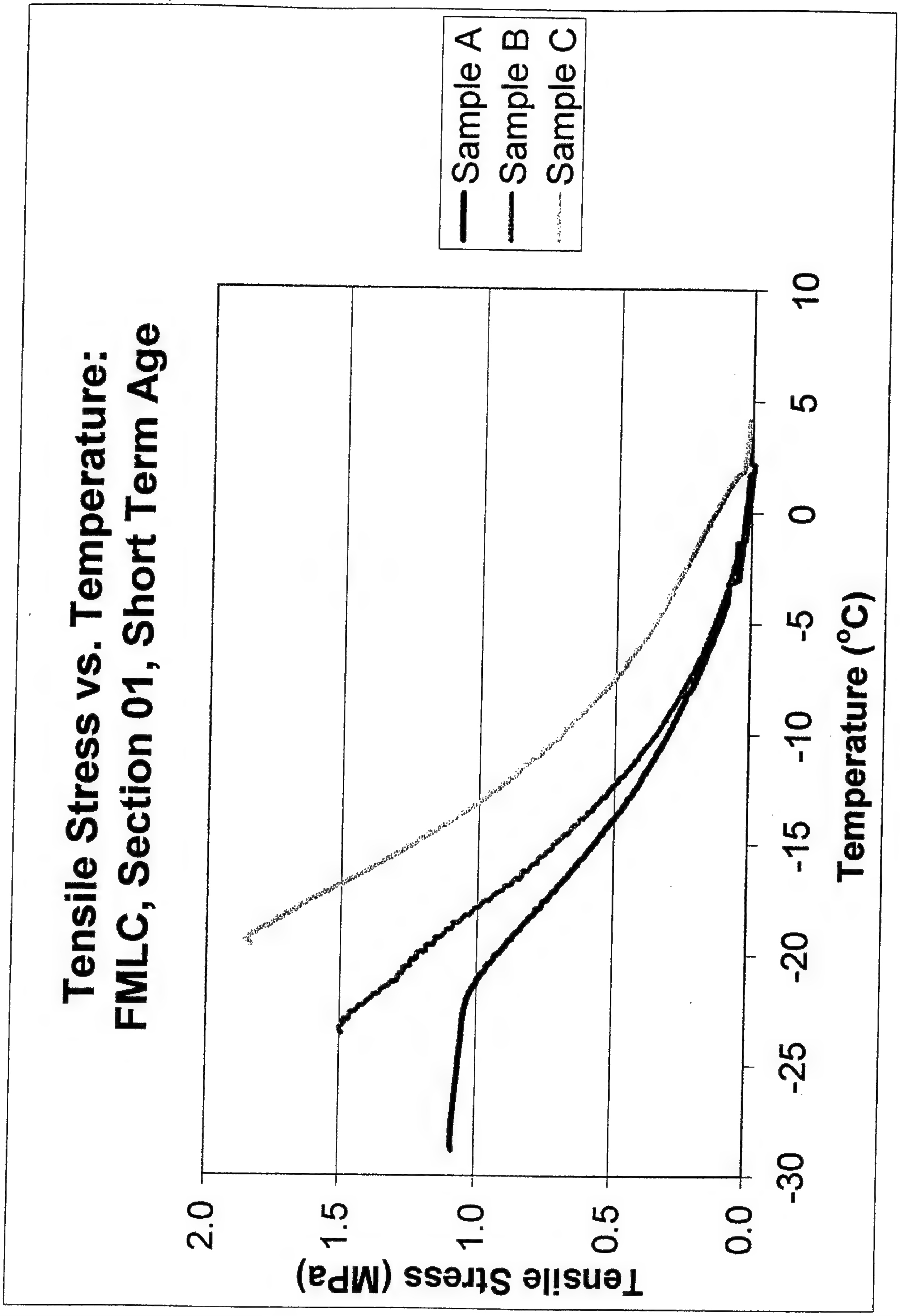
Tensile Stress vs. Temperature:
FMFC, Section 39, Short Term Age
Sample A
Sample B
Sample C
Tensile Stress (MPa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30
-25
-20
-15
-10
-5
0
5
Temperature (°C)

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMFC 39	A	4.2	2.62	380	-23.1	-9.6
	B	4.3	3.01	437	-25.4	-13.7
	C	3.0	3.32	481	-25.2	-13.4
	Mean	3.9	2.98	433	-24.6	-12.2
	Min	3.0	2.62	380	-23.1	-9.6
	Max	4.3	3.32	481	-25.4	-13.7

Appendix

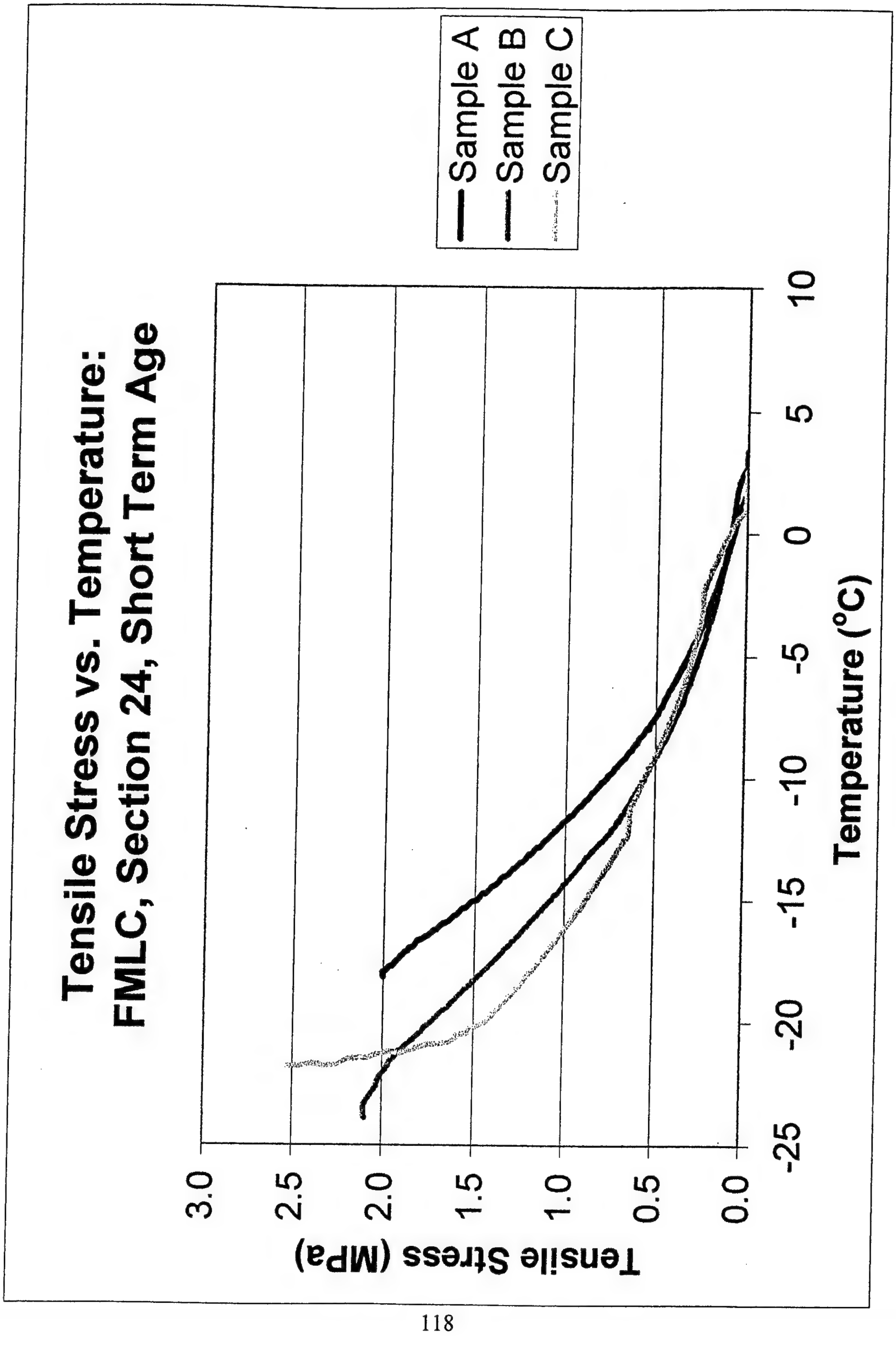
E

Individual FMLC TSRST Sample Data

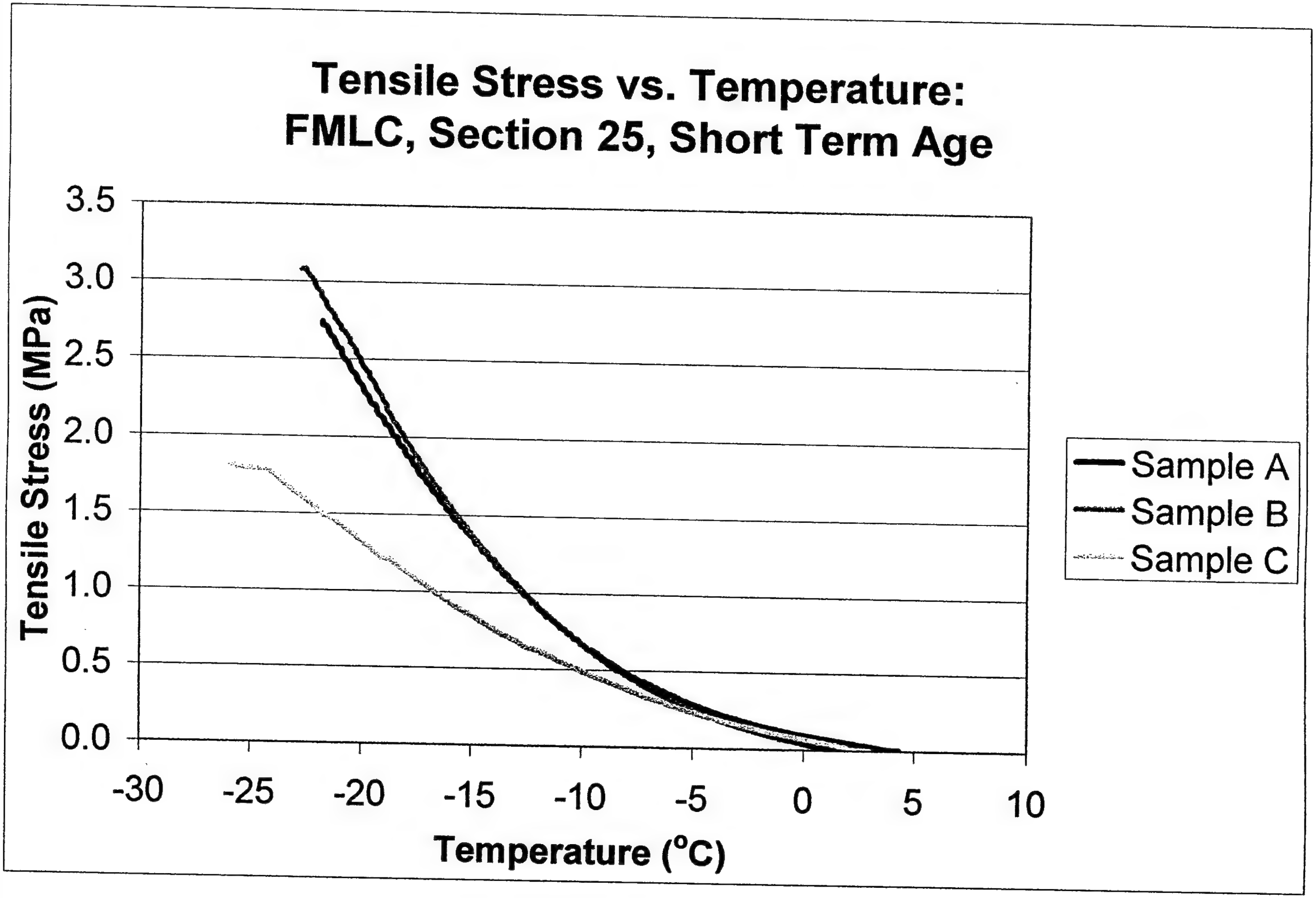


Tensile Stress vs. Temperature:
FMLC, Section 01, Short Term Age
Sample A
Sample B
Sample C
Tensile Stress (MPa)
2.0
1.5
1.0
0.5
0.0
-30
-25
-20
-15
-10
-5
0
5
10
Temperature (°C)

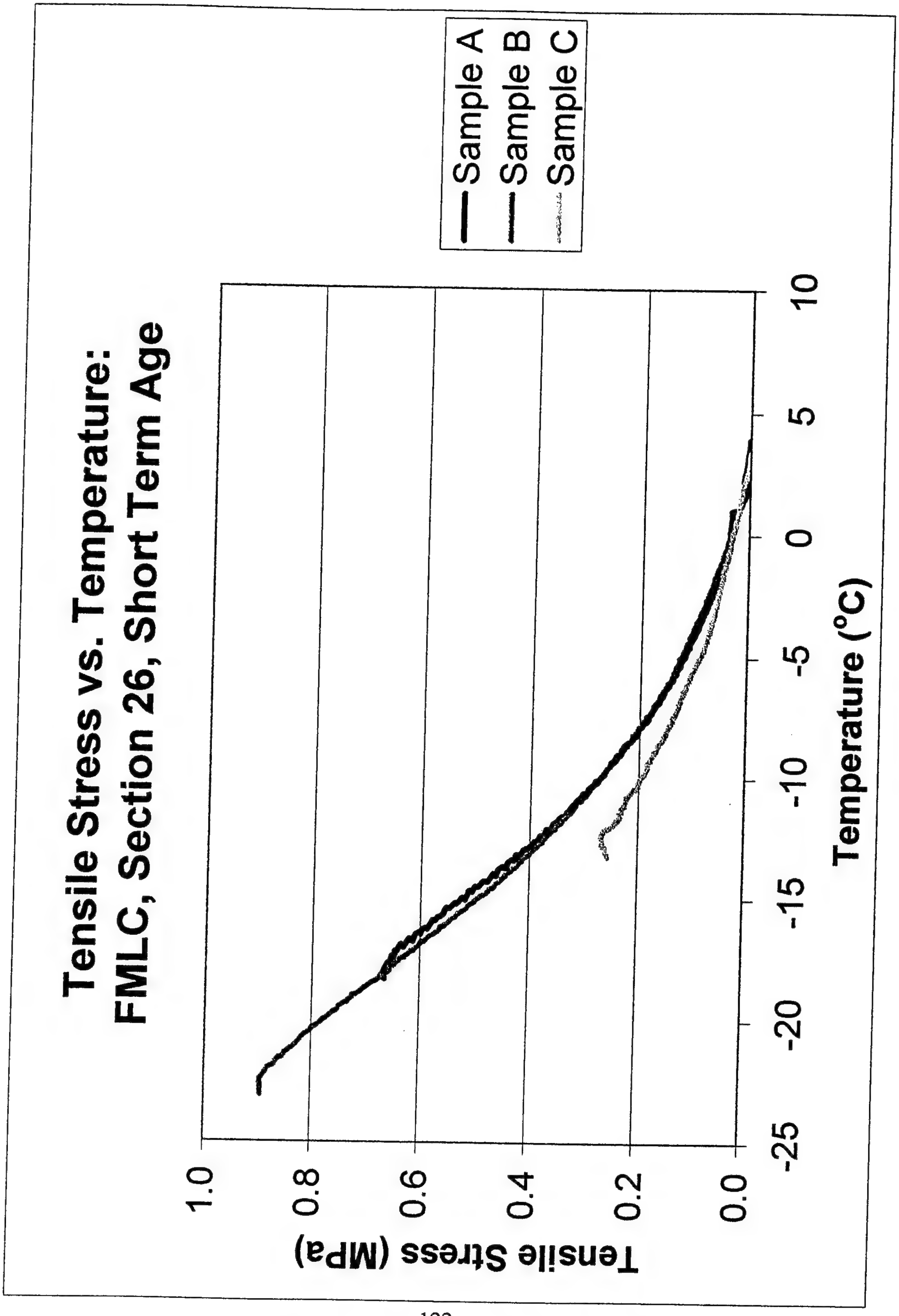
Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(^{o}C)	(^{o}F)
FMLC 01	A	8.7	1.08	157	-28.8	-19.8
	B	8.7	1.49	217	-23.6	-10.5
	C	9.5	1.84	266	-19.6	-3.3
	Mean	9.0	1.47	213	-24.0	-11.2
	Min	8.7	1.08	157	-19.6	-3.3
	Max	9.5	1.84	266	-28.8	-19.8


Tensile Stress vs. Temperature:
FMLC, Section 24, Short Term Age
Tensile Stress (MPa)
Temperature (°C)
Sample A
Sample B
Sample C
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
5
10

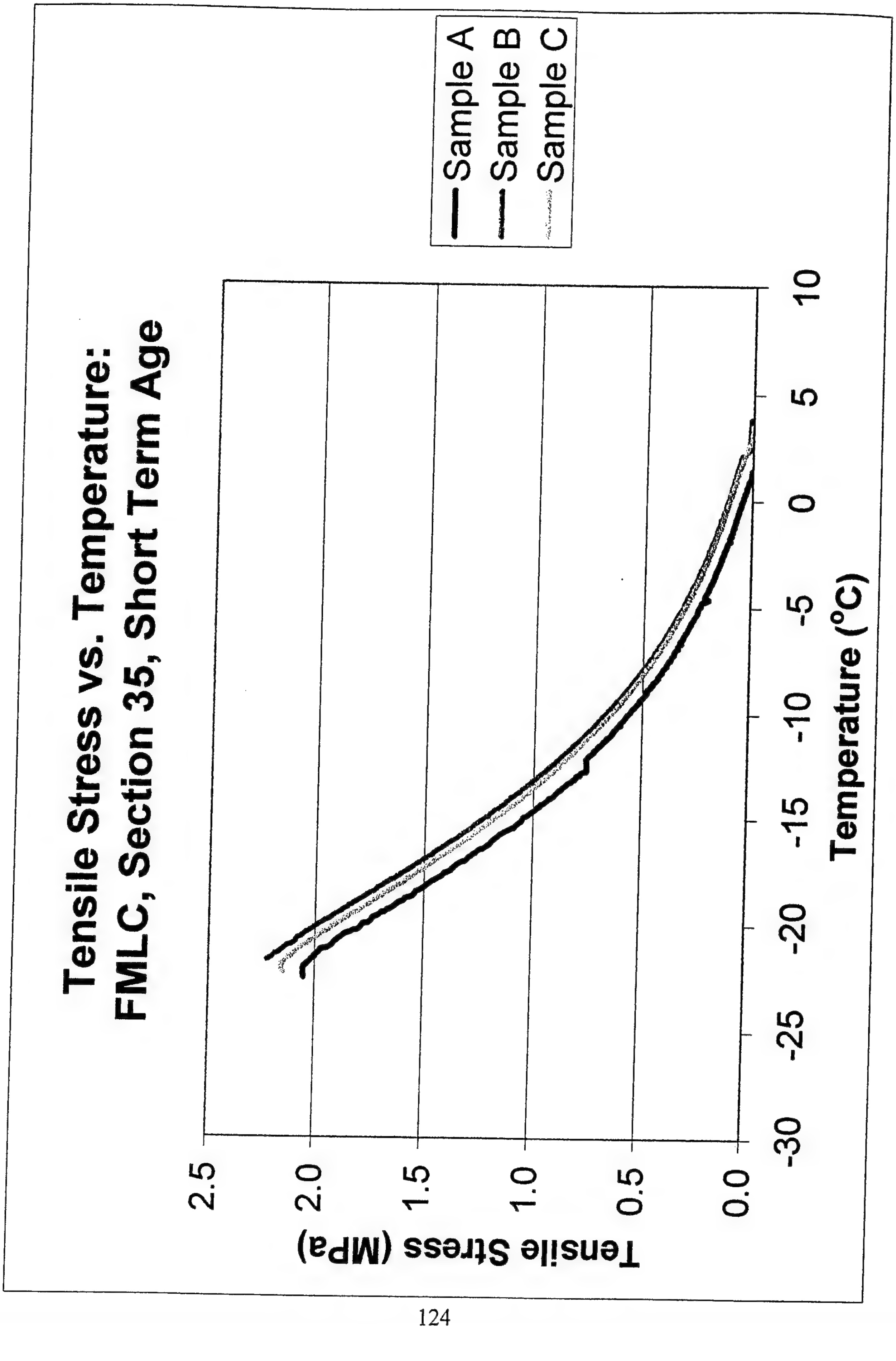
Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMLC 24	A	4.5	2.00	290	-18.2	-0.8
	B	5.0	2.09	304	-23.9	-11.0
	C	5.2	2.53	367	-21.8	-7.2
	Mean	4.9	2.21	320	-21.3	-6.3
	Min	4.5	2.00	290	-18.2	-0.8
	Max	5.2	2.53	367	-23.9	-11.0


Tensile Stress vs. Temperature:
FMLC, Section 25, Short Term Age
Tensile Stress (MPa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30
-25
-20
-15
-10
-5
0
5
10
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(^{o}C)	(^{o}F)
FMLC 25	A	2.5	2.74	398	-21.8	-7.2
	B	3.0	3.08	446	-22.8	-9.0
	C	3.6	1.81	262	-25.9	-14.6
	Mean	3.0	2.54	369	-23.5	-10.3
	Min	2.5	1.81	262	-21.8	-7.2
	Max	3.6	3.08	446	-25.9	-14.6

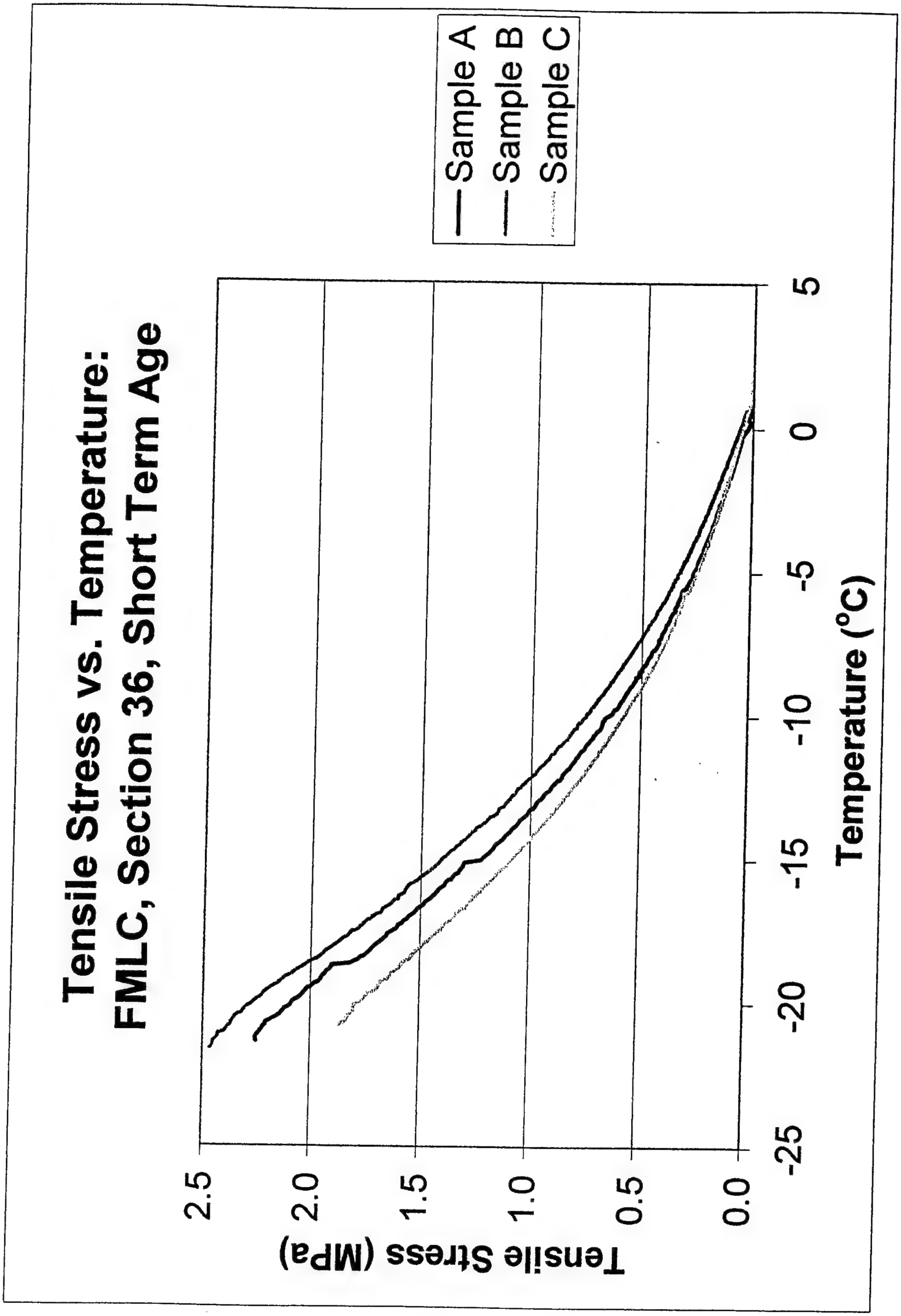

Tensile Stress vs. Temperature:
FMLC, Section 26, Short Term Age
Tensile Stress (MPa)
1.0
0.8
0.6
0.4
0.2
0.0
-25
-20
-15
-10
-5
0
5
10
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMLC 26	A	6.7	0.67	97	-18.3	-0.9
	B	7.3	0.90	130	-23.1	-9.6
	C	6.7	0.26	37	-13.3	8.1
	Mean	6.9	0.61	88	-18.2	-0.8
	Min	6.7	0.26	37	-13.3	8.1
	Max	7.3	0.90	130	-23.1	-9.6

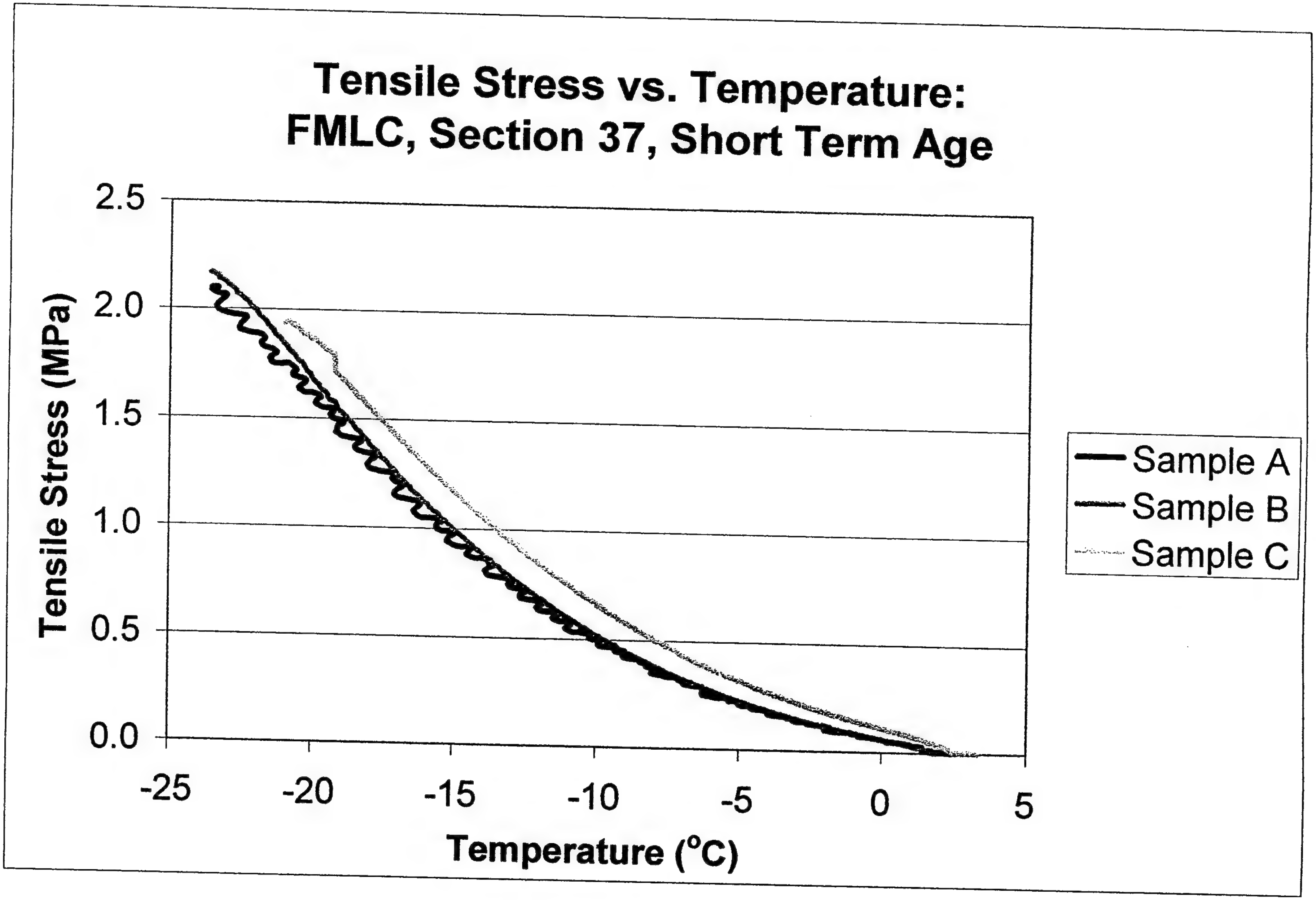


Tensile Stress vs. Temperature:
FMLC, Section 35, Short Term Age
Tensile Stress (MPa)
0.0
0.5
1.0
1.5
2.0
2.5
-30
-25
-20
-15
-10
-5
0
5
10
Temperature (°C)
Sample A
Sample B
Sample C

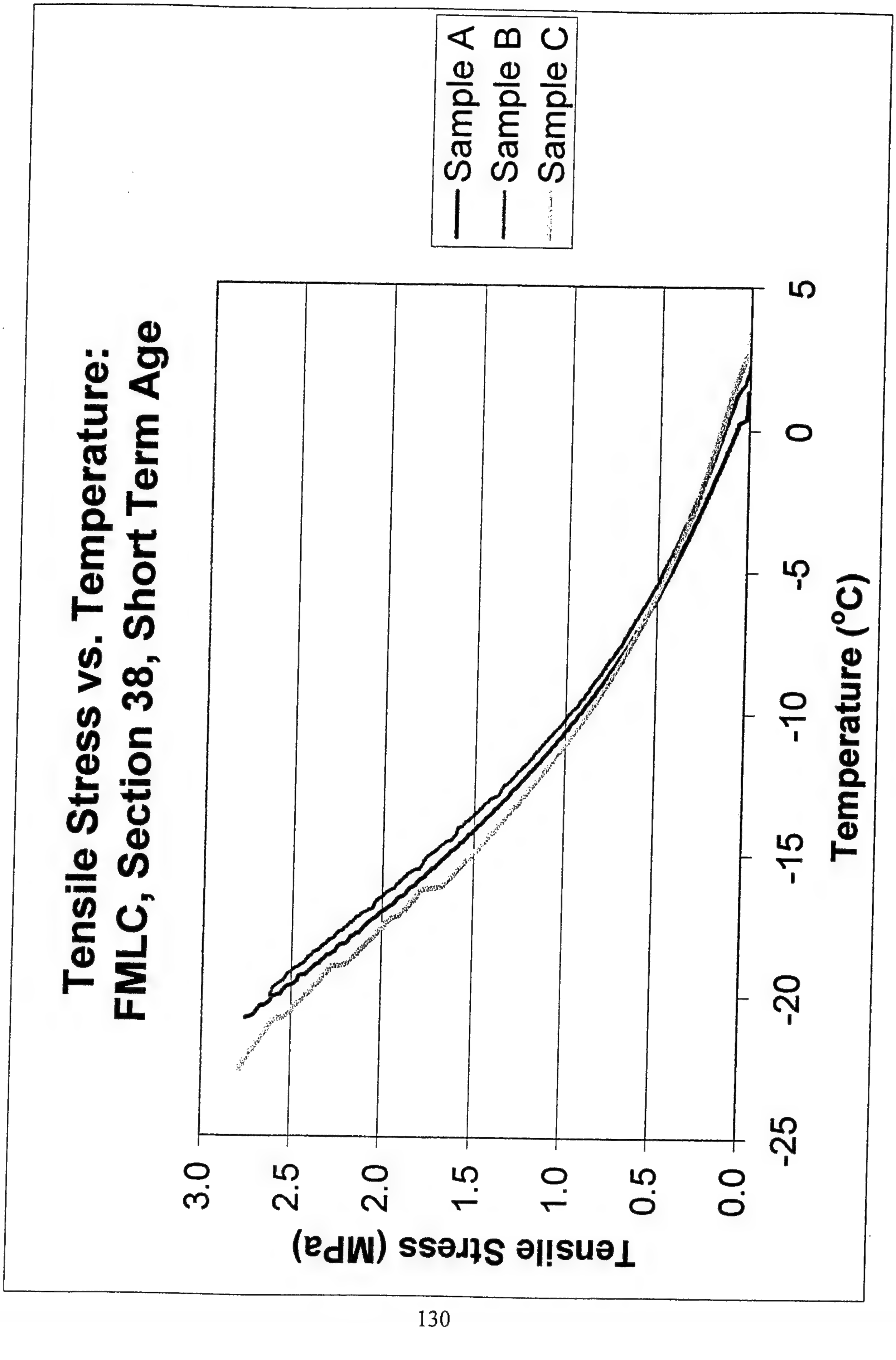
Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMLC 35	A	8.3	2.05	298	-22.5	-8.5
	B	7.5	2.23	323	-21.7	-7.1
	C	7.5	2.15	312	-22.3	-8.1
	Mean	7.8	2.14	311	-22.2	-7.9
	Min	7.5	2.05	298	-21.7	-7.1
	Max	8.3	2.23	323	-22.5	-8.5


Tensile Stress vs. Temperature:
FMLC, Section 36, Short Term Age
Tensile Stress (MPa)
2.5
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
5
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMLC 36	A	8.0	1.87	271	-20.8	-5.4
	B	7.2	2.25	327	-21.4	-6.5
	C	7.5	2.47	358	-21.6	-6.9
	Mean	7.6	2.20	319	-21.3	-6.3
	Min	7.2	1.87	271	-20.8	-5.4
	Max	8.0	2.47	358	-21.6	-6.9

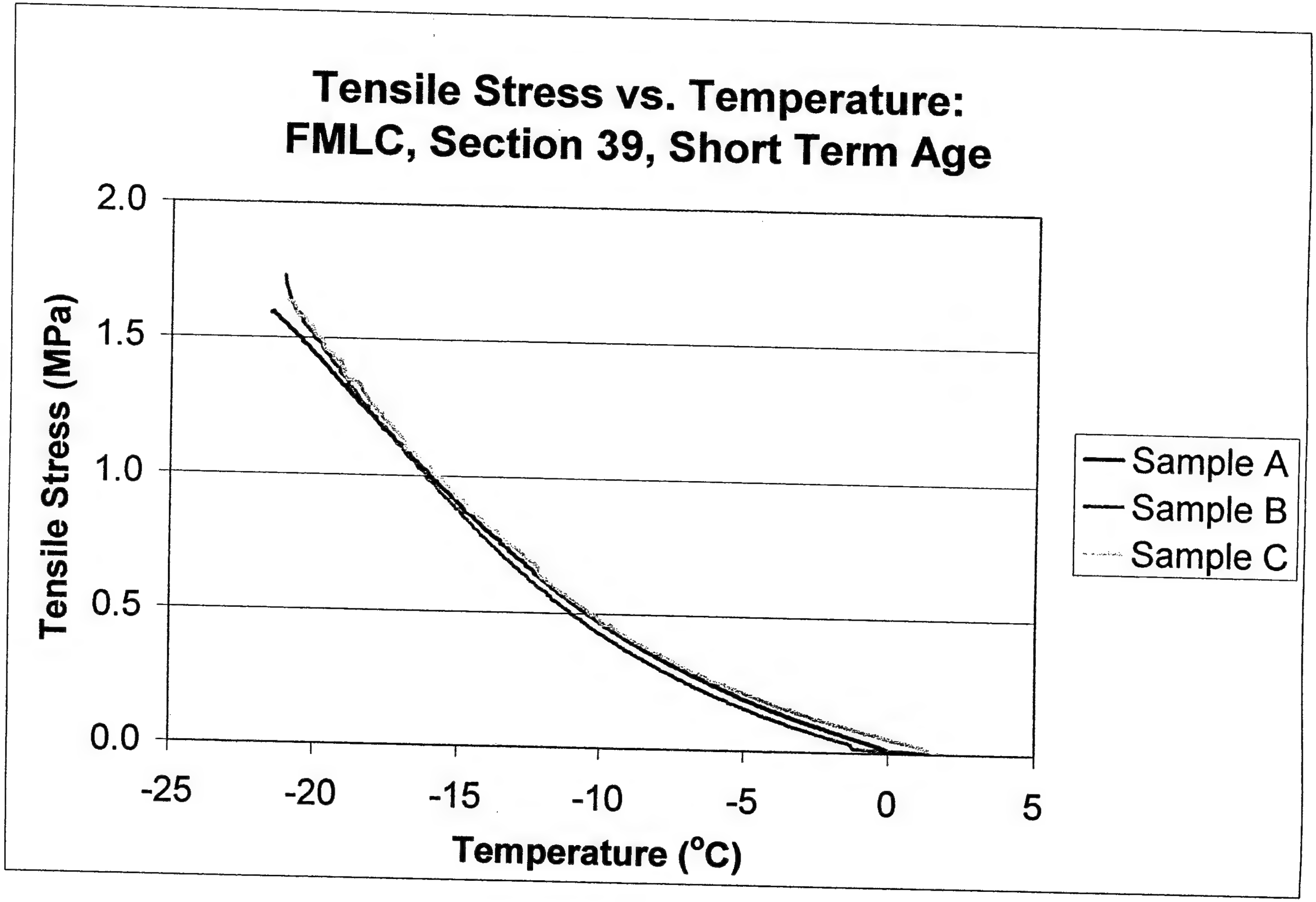

Tensile Stress vs. Temperature:
FMLC, Section 37, Short Term Age
Tensile Stress (MPa)
2.5
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
5
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMLC 37	A	7.0	2.17	315	-23.6	-10.5
	B	8.2	2.10	304	-23.6	-10.5
	C	7.5	1.94	281	-21.0	-5.8
	Mean	7.6	2.07	300	-22.7	-8.9
	Min	7.0	1.94	281	-21.0	-5.8
	Max	8.2	2.17	315	-23.6	-10.5



Tensile Stress vs. Temperature:
FMLC, Section 38, Short Term Age
Tensile Stress (MPa)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
5
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMLC 38	A	8.7	2.75	399	-21.0	-5.8
	B	8.9	2.62	380	-20.1	-4.2
	C	6.7	2.79	404	-22.7	-8.9
	Mean	8.1	2.72	394	-21.3	-6.3
	Min	6.7	2.62	380	-20.1	-4.2
	Max	8.9	2.79	404	-22.7	-8.9

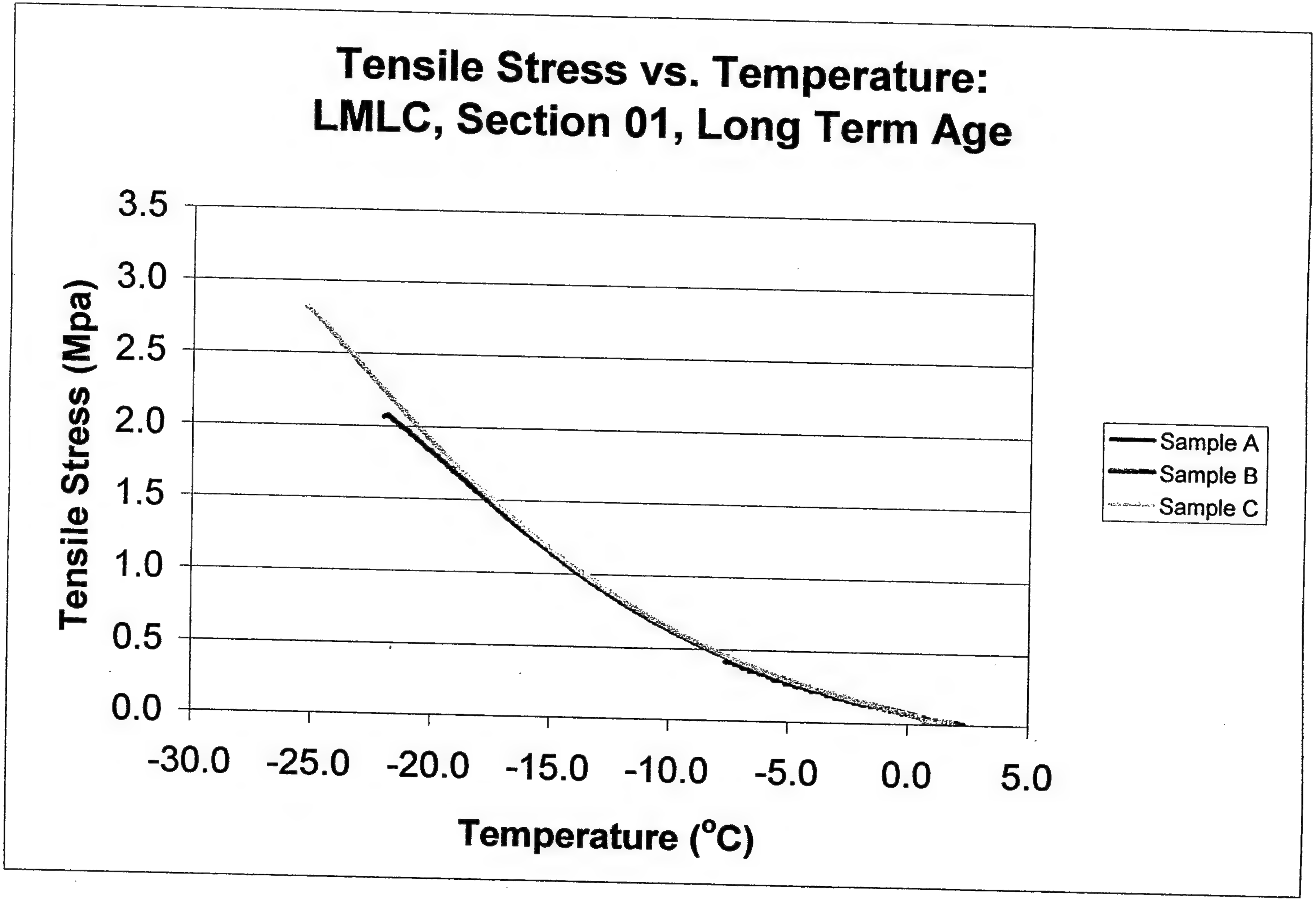

Tensile Stress vs. Temperature:
FMLC, Section 39, Short Term Age
Tensile Stress (MPa)
2.0
1.5
1.0
0.5
0.0
-25
-20
-15
-10
-5
0
5
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
FMLC 39	A	8.2	1.60	232	-21.5	-6.7
	B	7.9	1.64	238	-21.0	-5.8
	C	8.2	1.73	251	-21.1	-6.0
	Mean	8.1	1.66	240	-21.2	-6.2
	Min	7.9	1.60	232	-21.0	-5.8
	Max	8.2	1.73	251	-21.5	-6.7

Appendix

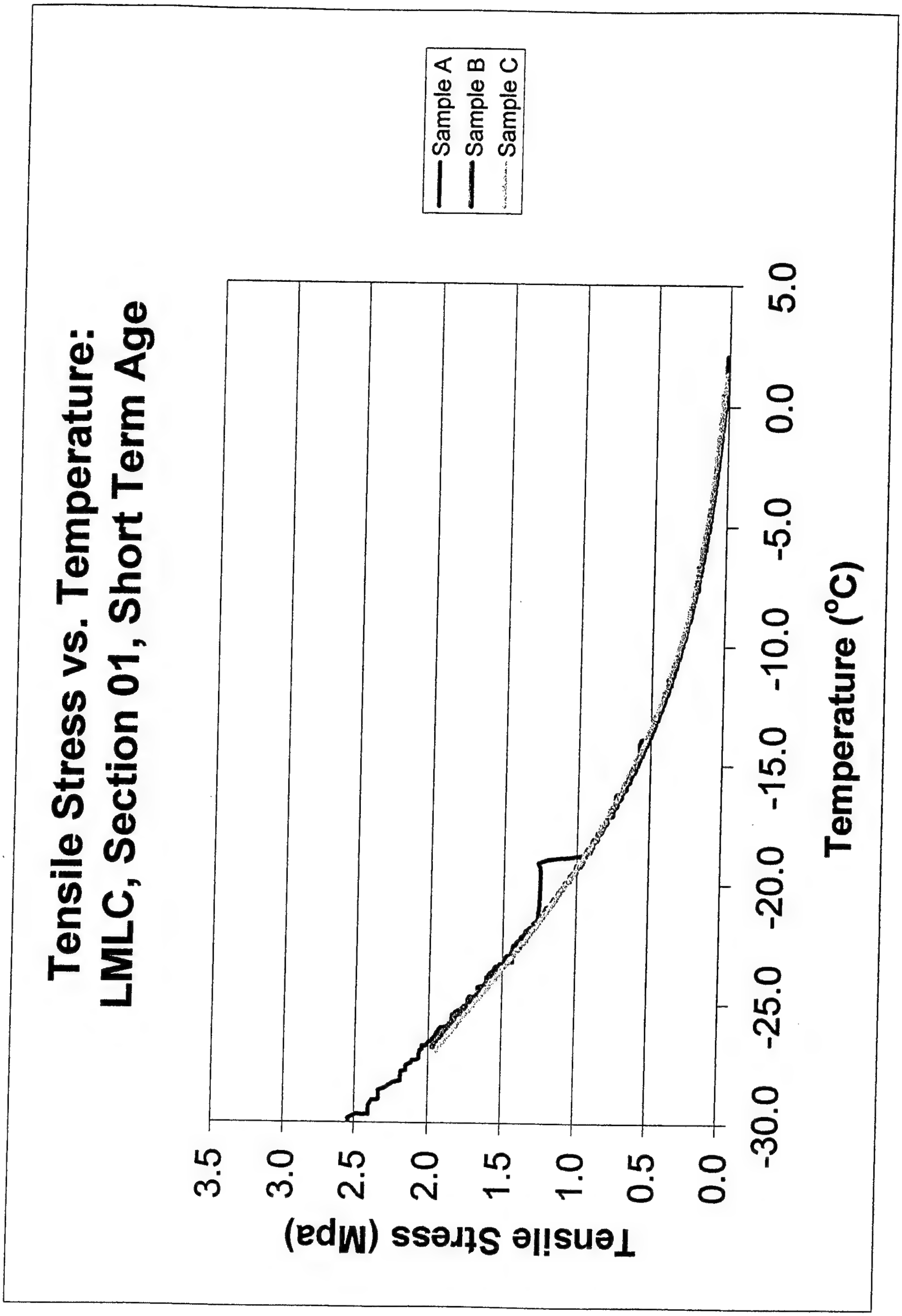
F

Individual LMLC TSRST Sample Data



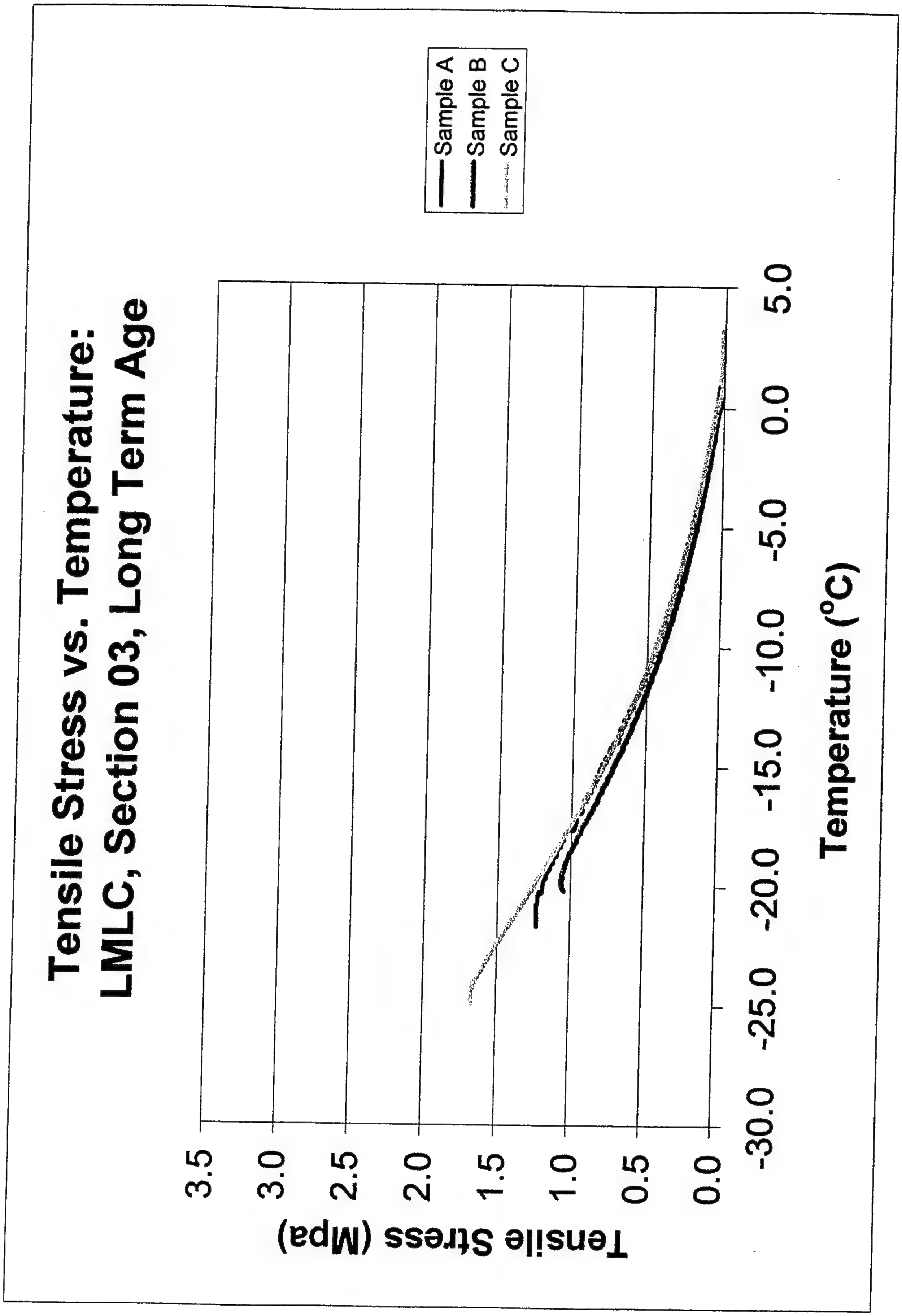
Tensile Stress vs. Temperature:
LMLC, Section 01, Long Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample B	8.18	2.07	301	-22.0	-7.6
	Sample C	8.33	2.82	409	-25.3	-13.5
Section 01 L	Mean	8.26	2.45	355	-23.7	-10.6
	Min	8.18	2.07	301	-22.0	-7.6
	Max	8.33	2.82	409	-25.3	-13.5

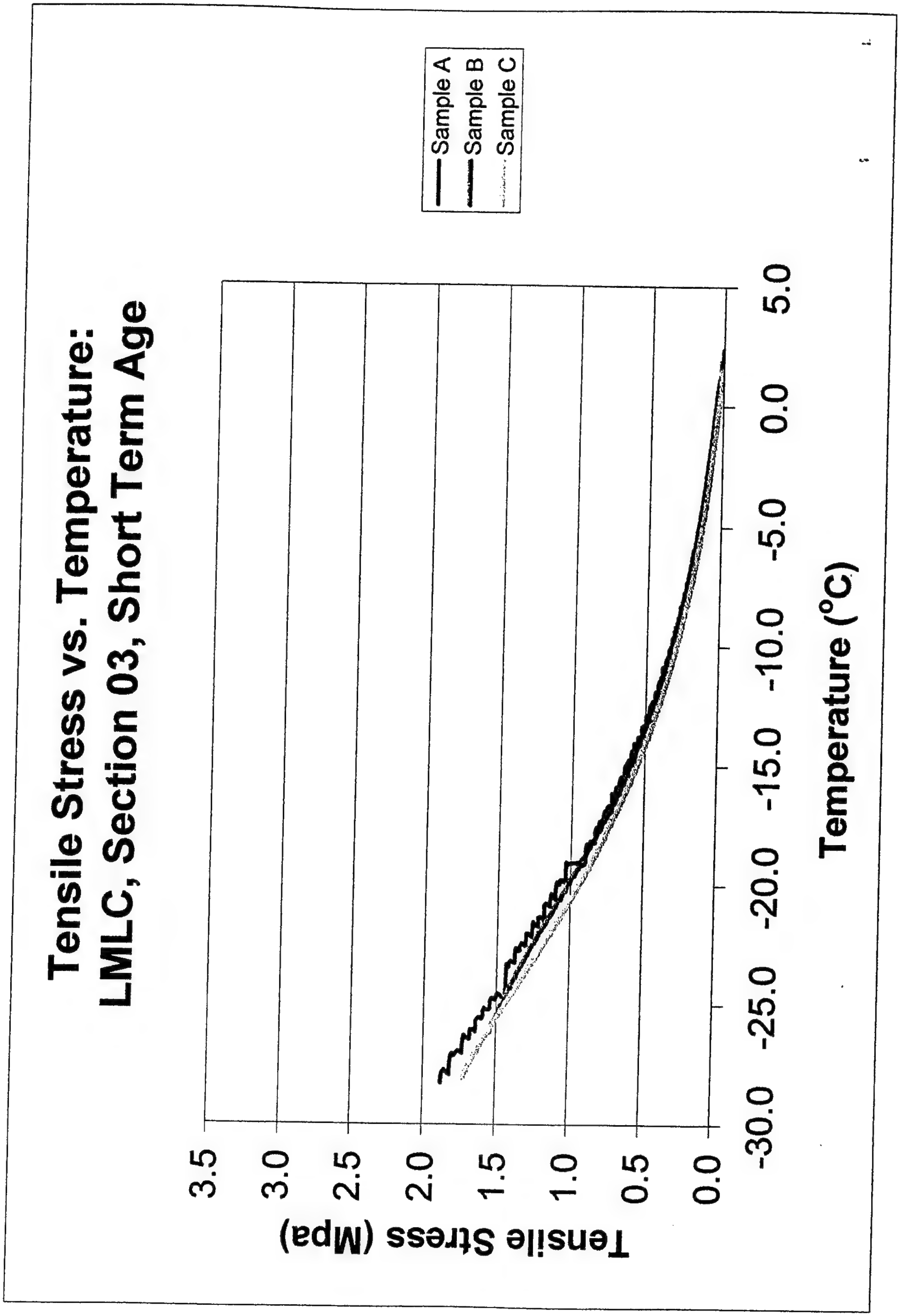


Tensile Stress vs. Temperature:
LMLC, Section 01, Short Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	8.95	2.54	369	-30.1	-22.1
	Sample B	8.20	1.98	287	-26.8	-16.3
	Sample C	8.37	1.95	282	-27.0	-16.5
Section 01 S	Mean	8.51	2.16	313	-28.0	-18.3
	Min	8.20	1.95	282	-26.8	-16.3
	Max	8.95	2.54	369	-30.1	-22.1

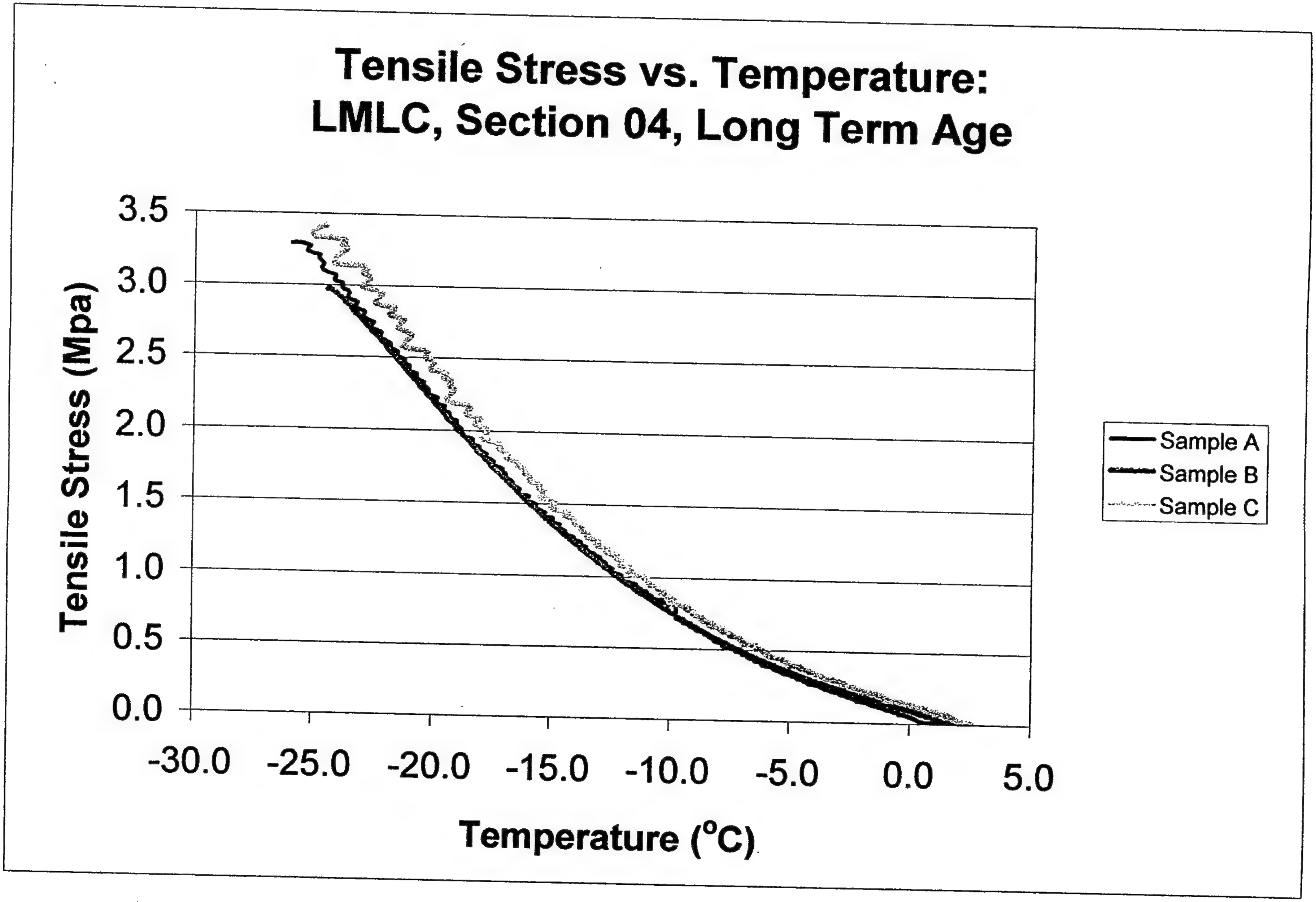

Tensile Stress vs. Temperature:
LMLC, Section 03, Long Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	13.00	1.23	179	-21.7	-7.0
	Sample B	12.55	1.07	155	-20.2	-4.3
	Sample C	12.76	1.67	243	-24.9	-12.8
Section 03 L	Mean	12.77	1.33	192	-22.2	-8.0
	Min	12.55	1.07	155	-20.2	-4.3
	Max	13.00	1.67	243	-24.9	-12.8

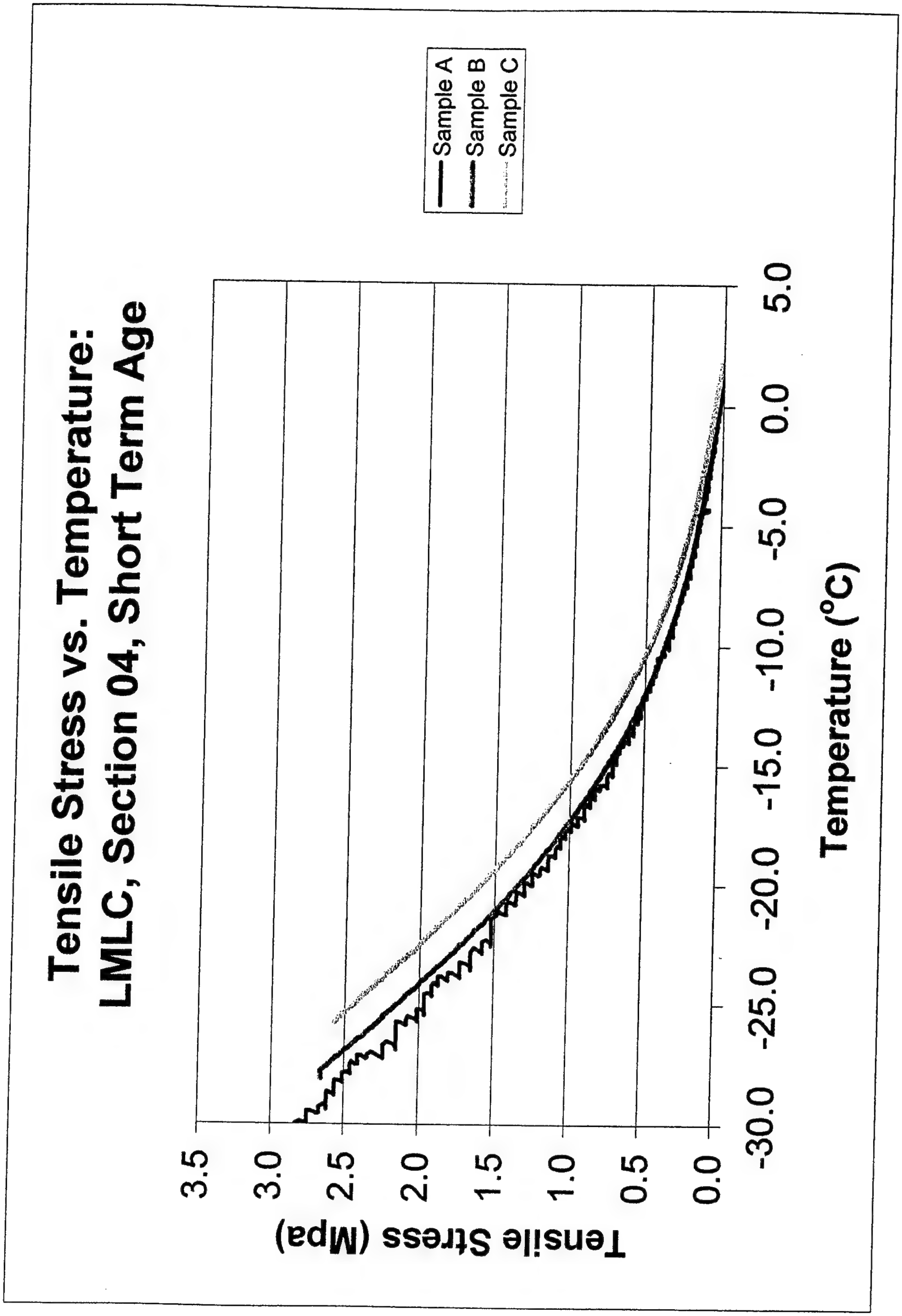


Tensile Stress vs. Temperature:
LMLC, Section 03, Short Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	12.63	1.88	272	-28.3	-18.9
	Sample B	11.75	1.55	224	-26.1	-15.0
	Sample C	12.80	1.73	251	-28.1	-18.6
Section 03 S	Mean	12.39	1.72	249	-27.5	-17.5
	Min	11.75	1.55	224	-26.1	-15.0
	Max	12.80	1.88	272	-28.3	-18.9

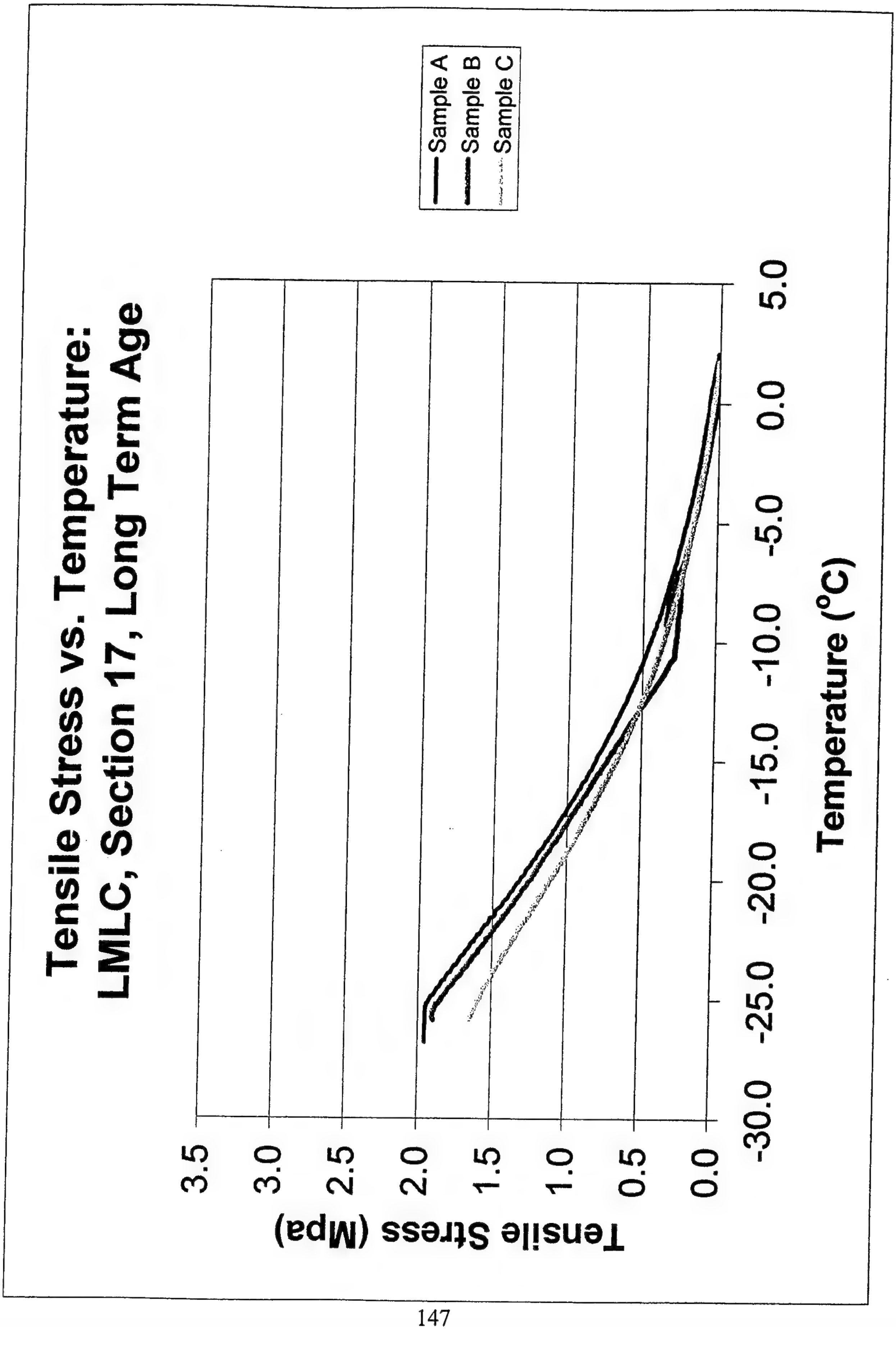

Tensile Stress vs. Temperature:
LMLC, Section 04, Long Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	4.98	3.29	478	-25.9	-14.7
	Sample B	4.73	2.97	431	-24.4	-12.0
	Sample C	3.93	3.42	495	-25.1	-13.1
Section 04 L	Mean	4.55	3.23	468	-25.1	-13.3
	Min	3.93	2.97	431	-24.4	-12.0
	Max	4.98	3.42	495	-25.9	-14.7

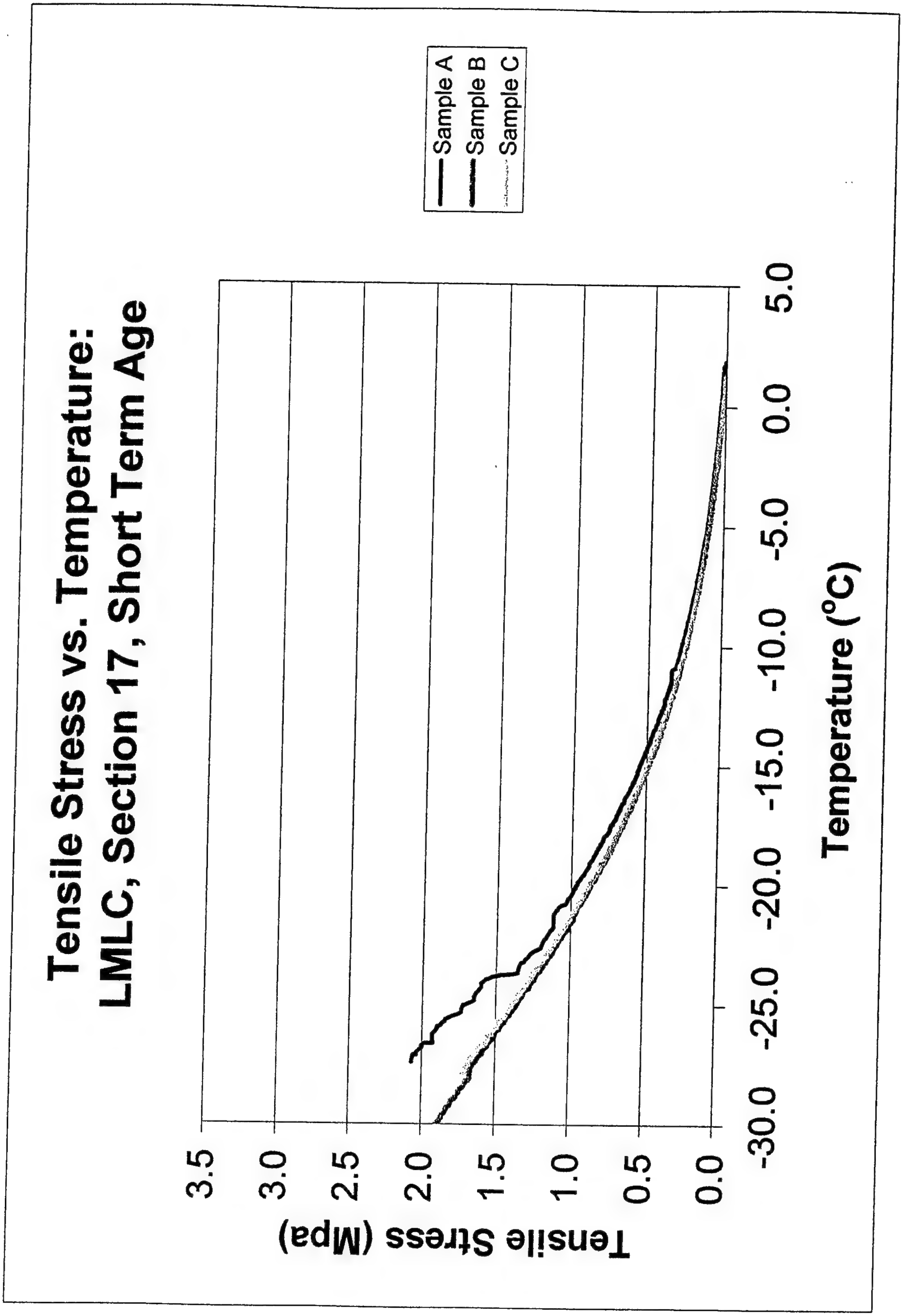


Tensile Stress vs. Temperature:
LMLC, Section 04, Short Term Age
Sample A
Sample B
Sample C
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)

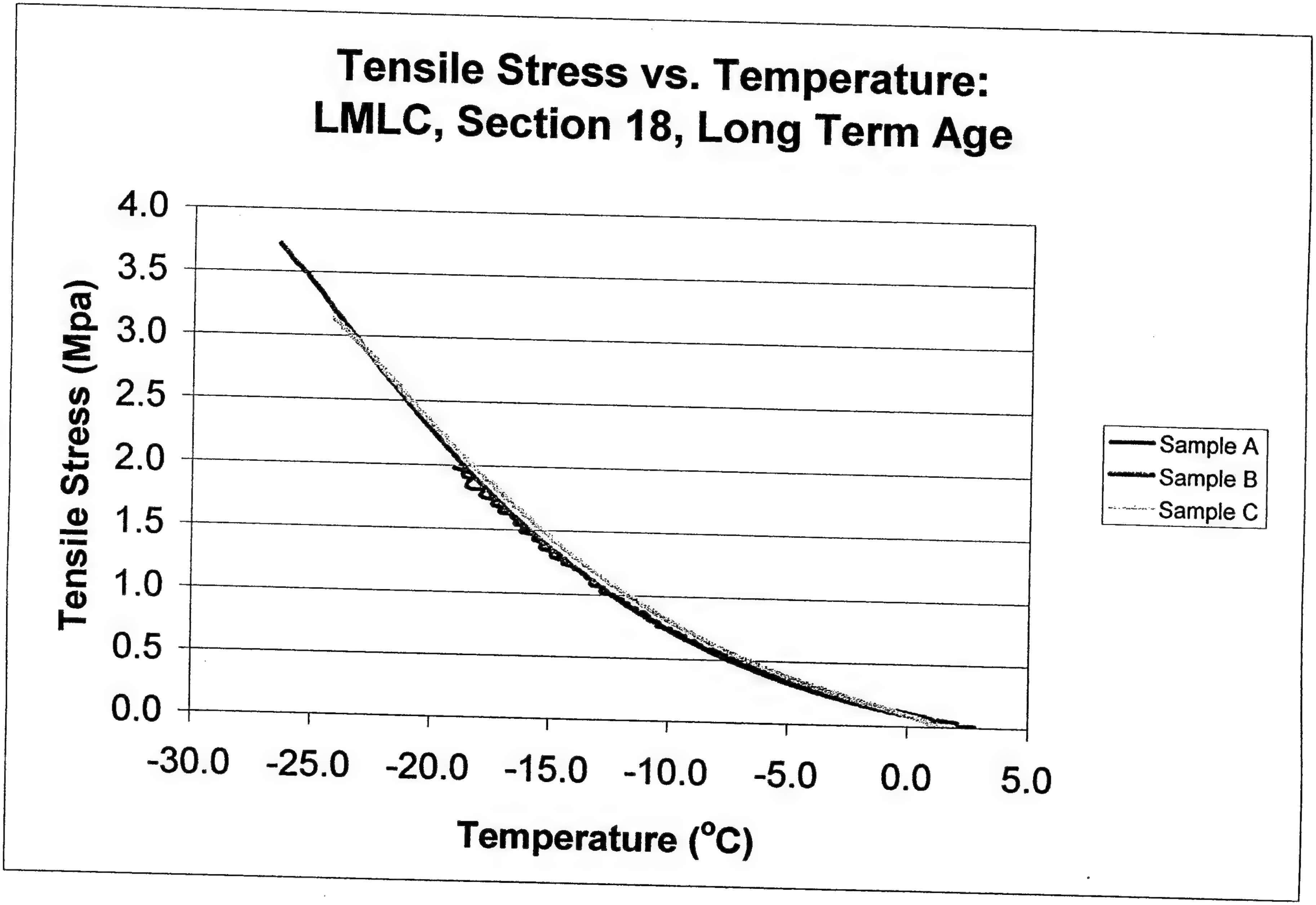
Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	4.98	3.42	496	-33.6	-28.4
	Sample B	4.98	2.66	386	-28.1	-18.6
	Sample C	4.27	2.58	374	-25.8	-14.4
Section 04 S	Mean	4.74	2.89	419	-29.2	-20.5
	Min	4.27	2.58	374	-25.8	-14.4
	Max	4.98	3.42	496	-33.6	-28.4


Tensile Stress vs. Temperature:
LMLC, Section 17, Long Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	11.75	1.95	284	-26.8	-16.2
	Sample B	12.81	1.90	276	-25.9	-14.6
	Sample C	12.60	1.65	239	-25.8	-14.5
Section 17 L	Mean	12.39	1.84	266	-26.2	-15.1
	Min	11.75	1.65	239	-25.8	-14.5
	Max	12.81	1.95	284	-26.8	-16.2

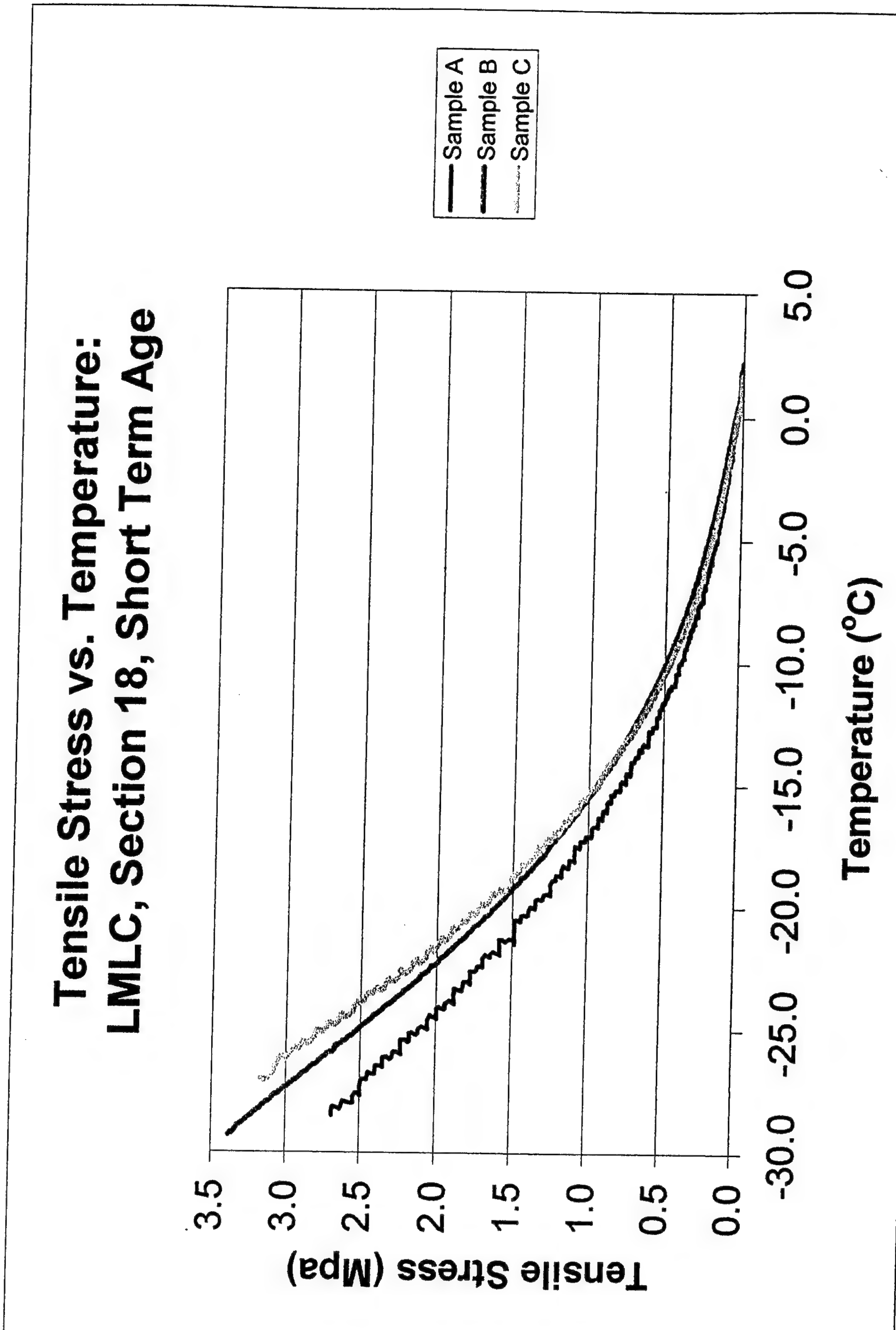

Tensile Stress vs. Temperature:
LMLC, Section 17, Short Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	12.67	2.07	301	-27.4	-17.3
	Sample B	11.88	1.90	275	-30.1	-22.2
	Sample C	11.85	1.72	249	-27.9	-18.2
Section 17 S	Mean	12.13	1.90	275	-28.5	-19.2
	Min	11.85	1.72	249	-27.4	-17.3
	Max	12.67	2.07	301	-30.1	-22.2

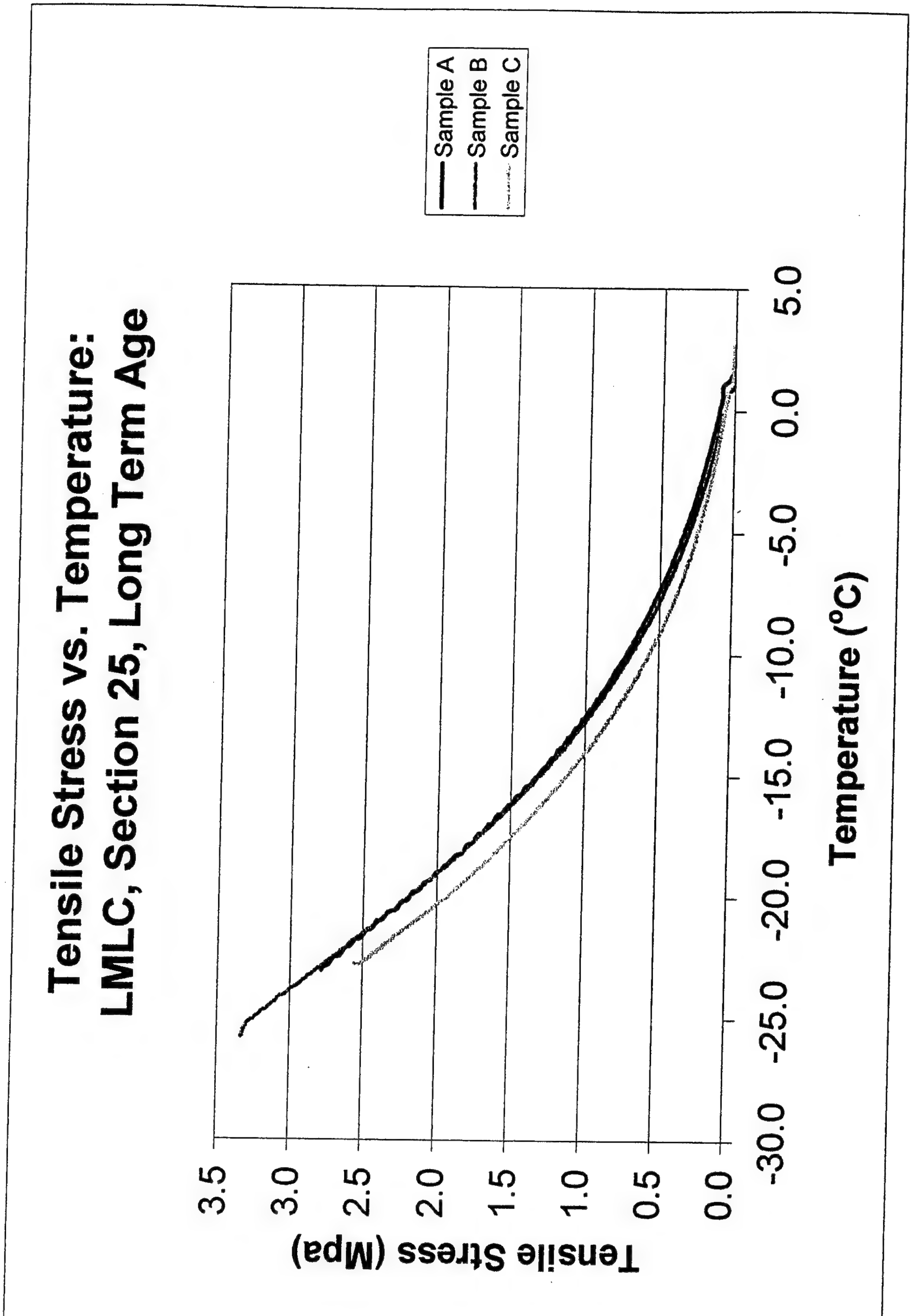


Tensile Stress vs. Temperature:
LMLC, Section 18, Long Term Age
Tensile Stress (Mpa)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	4.67	1.98	287	-19.0	-2.3
	Sample B	4.84	3.72	539	-26.4	-15.6
	Sample C	4.00	3.13	454	-24.2	-11.5
Section 18 L	Mean	4.50	2.94	427	-23.2	-9.8
	Min	4.00	1.98	287	-19.0	-2.3
	Max	4.84	3.72	539	-26.4	-15.6

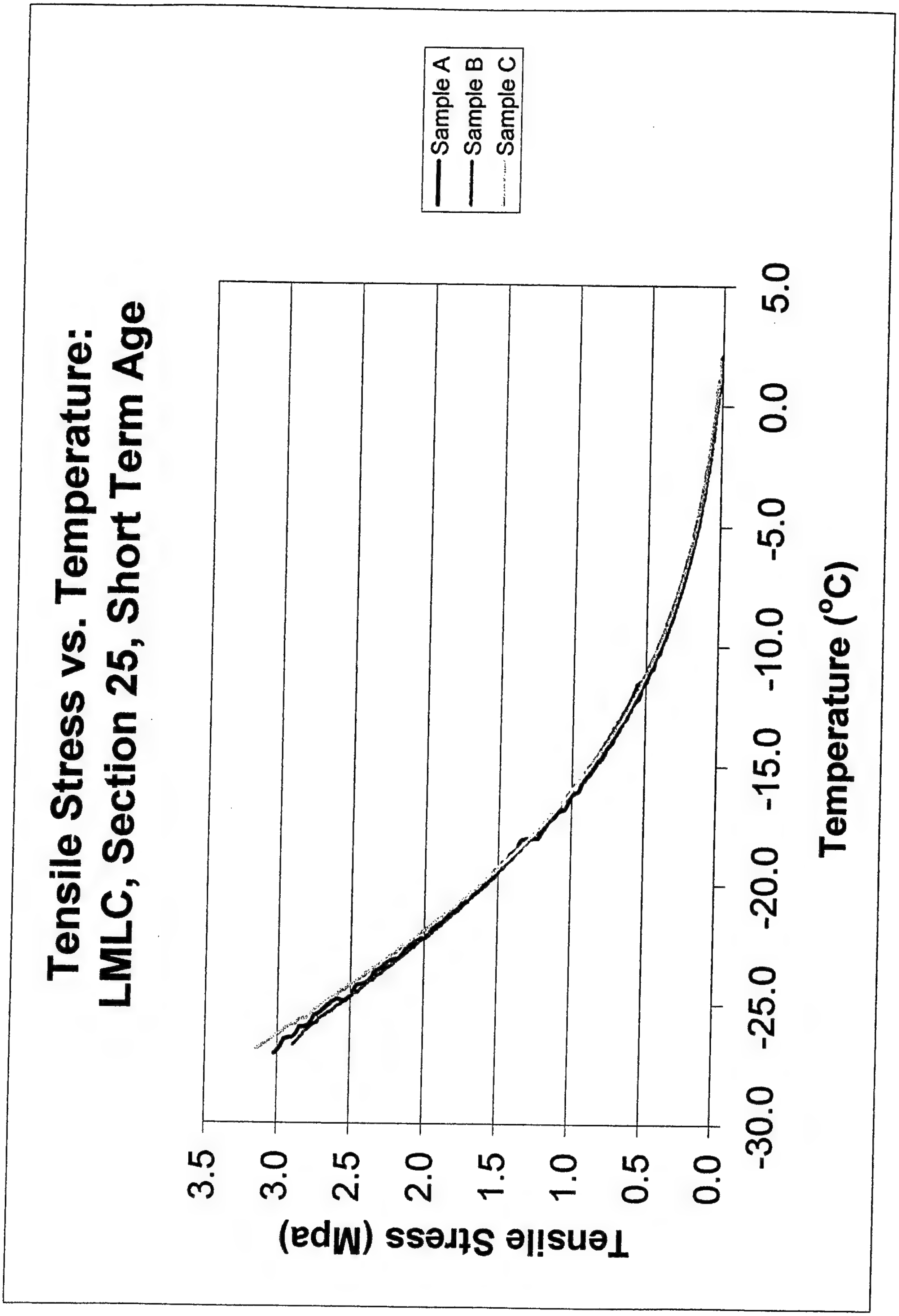

Tensile Stress vs. Temperature:
LMLC, Section 18, Short Term Age
Sample A
Sample B
Sample C
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	4.04	2.69	390	-28.5	-19.3
	Sample B	4.80	3.38	491	-29.3	-20.7
	Sample C	4.93	3.17	460	-27.1	-16.7
Section 18 S	Mean	4.59	3.08	447	-28.3	-18.9
	Min	4.04	2.69	390	-27.1	-16.7
	Max	4.93	3.38	491	-29.3	-20.7

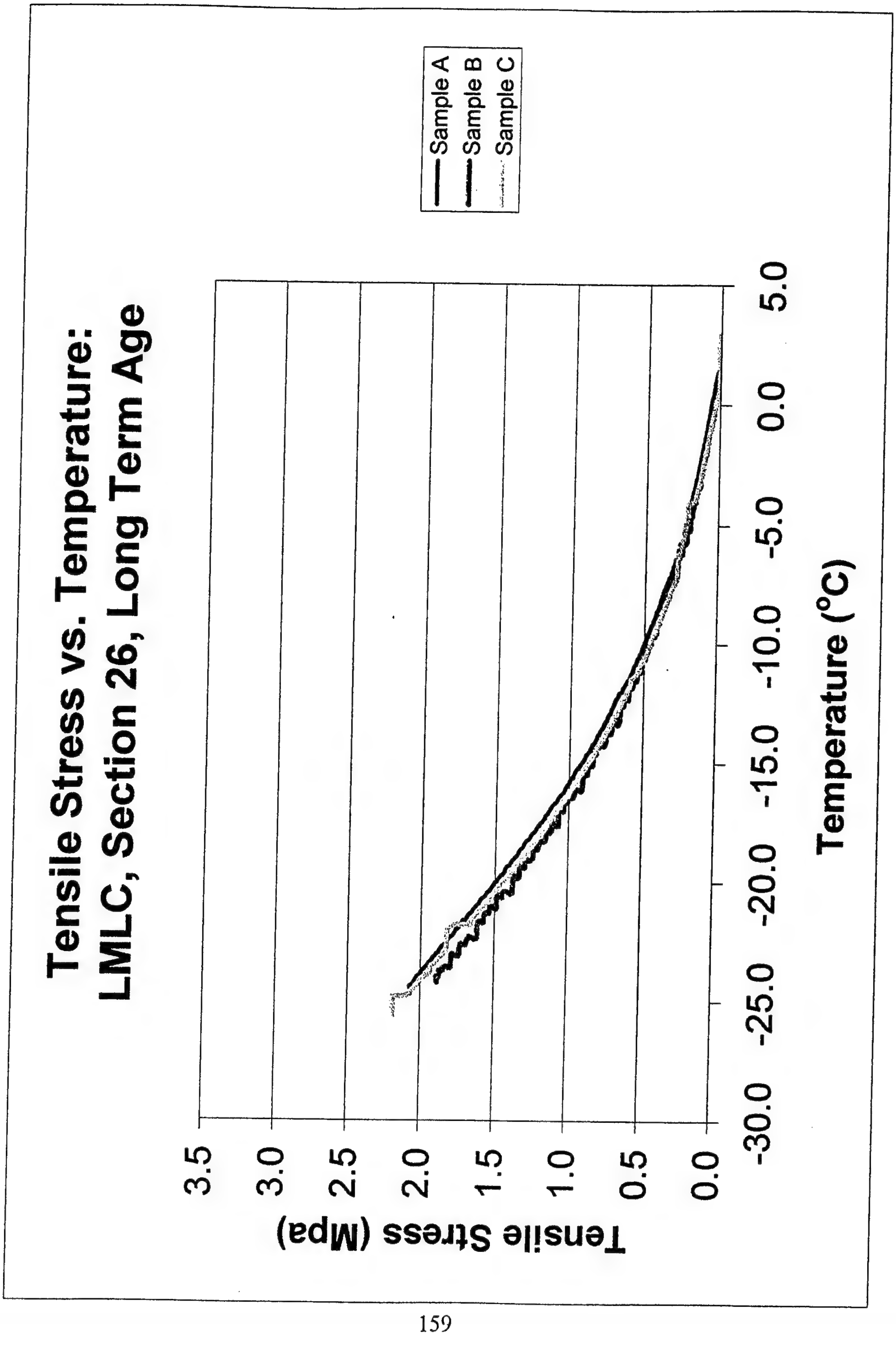


Tensile Stress vs. Temperature:
LMLC, Section 25, Long Term Age
Sample A
Sample B
Sample C
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	3.91	2.79	404	-23.1	-9.5
	Sample B	4.25	3.34	484	-25.8	-14.4
	Sample C	3.91	2.83	410	-32.4	-26.3
Section 25 L	Mean	4.02	2.98	433	-27.1	-16.7
	Min	3.91	2.79	404	-23.1	-9.5
	Max	4.25	3.34	484	-32.4	-26.3

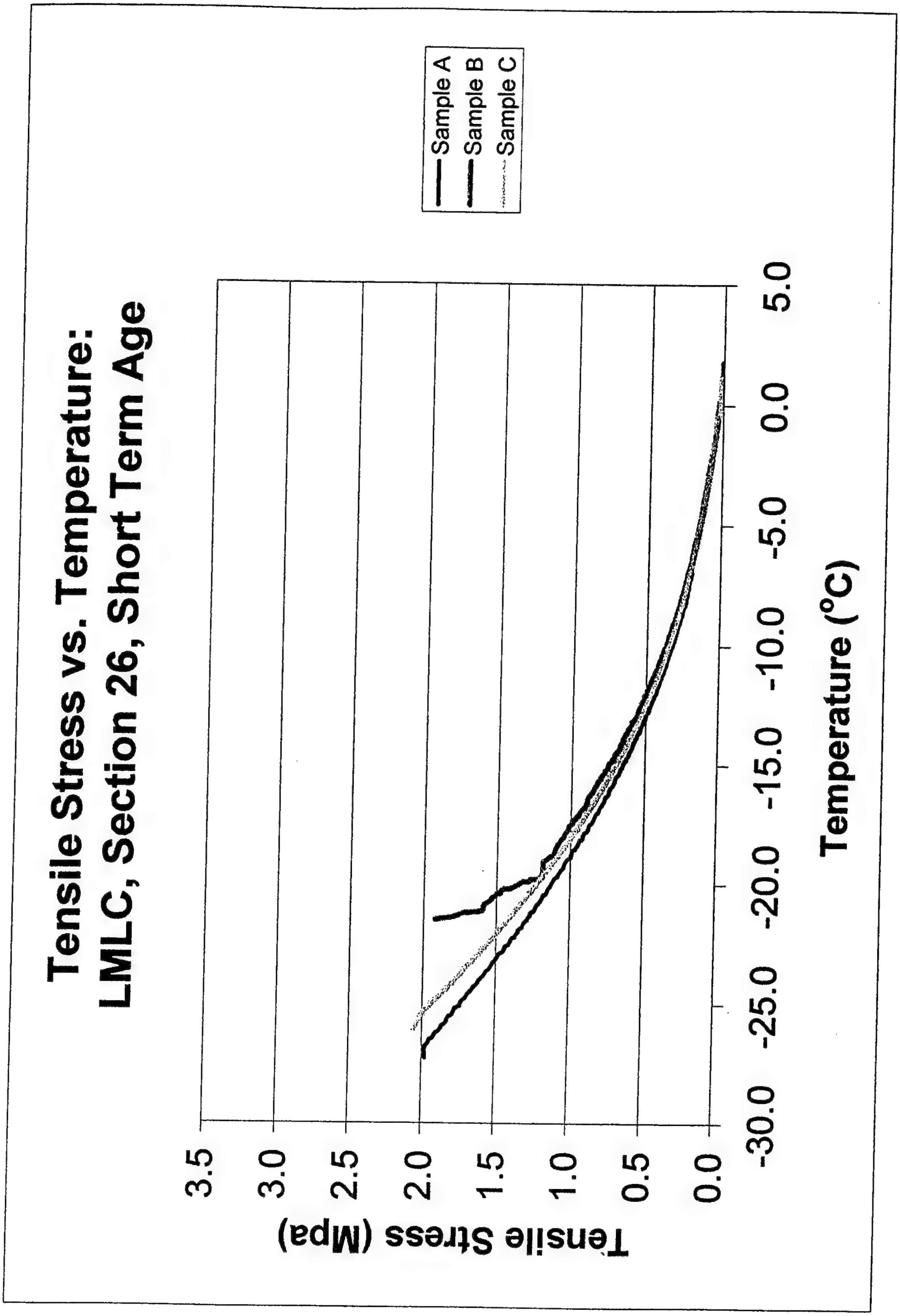

Tensile Stress vs. Temperature:
LMLC, Section 25, Short Term Age
Sample A
Sample B
Sample C
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	4.67	3.02	439	-27.1	-16.8
	Sample B	4.71	2.89	420	-26.7	-16.1
	Sample C	5.00	3.15	456	-26.9	-16.4
Section 25 S	Mean	4.79	3.02	438	-26.9	-16.4
	Min	4.67	2.89	420	-26.7	-16.1
	Max	5.00	3.15	456	-27.1	-16.8

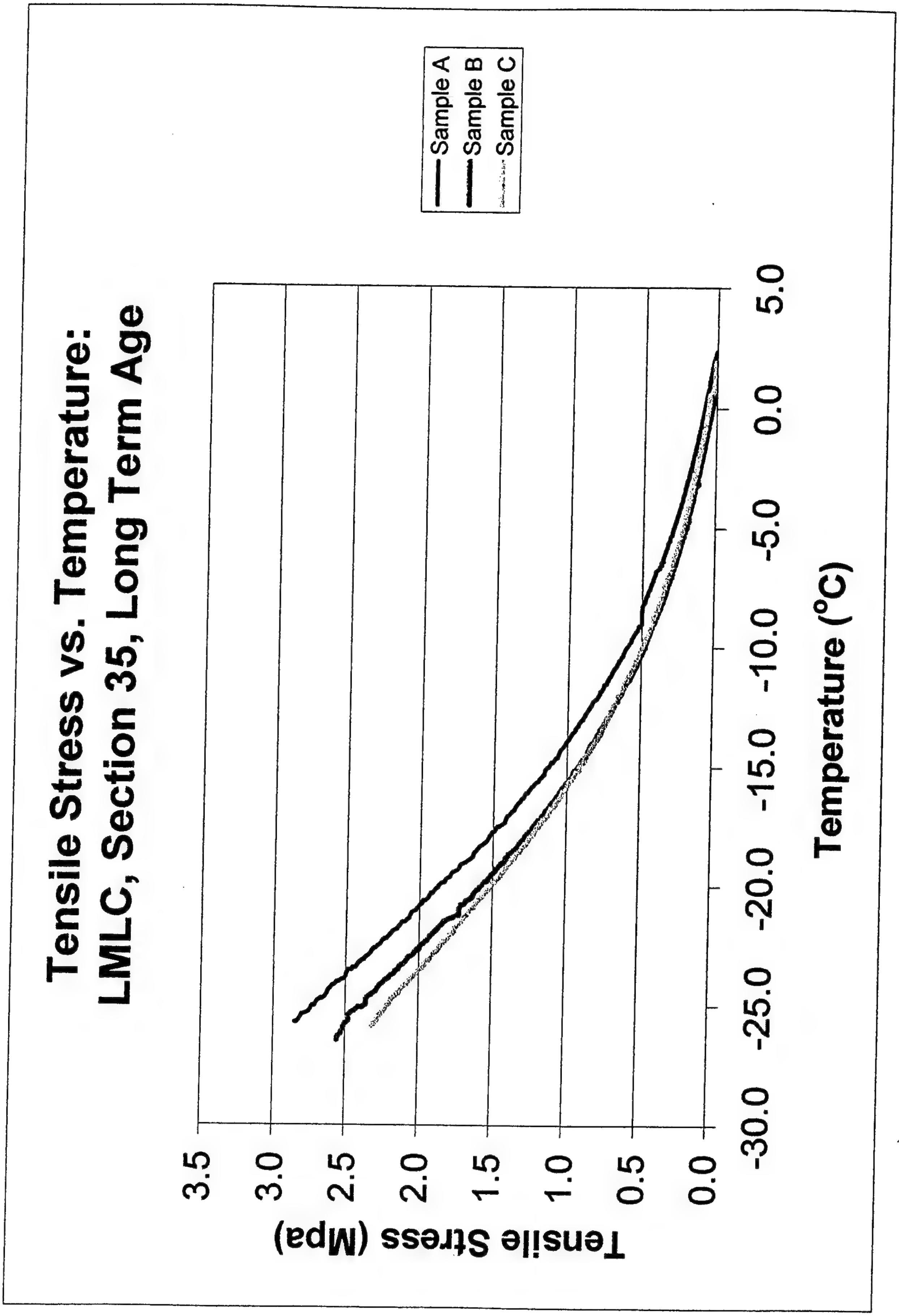


Tensile Stress vs. Temperature:
LMLC, Section 26, Long Term Age
Sample A
Sample B
Sample C
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	12.43	2.08	301	-24.7	-12.5
	Sample B	12.88	1.89	275	-24.2	-11.6
	Sample C	12.26	2.19	318	-25.6	-14.1
Section 26 L	Mean	12.52	2.05	298	-24.8	-12.7
	Min	12.26	1.89	275	-24.2	-11.6
	Max	12.88	2.19	318	-25.6	-14.1

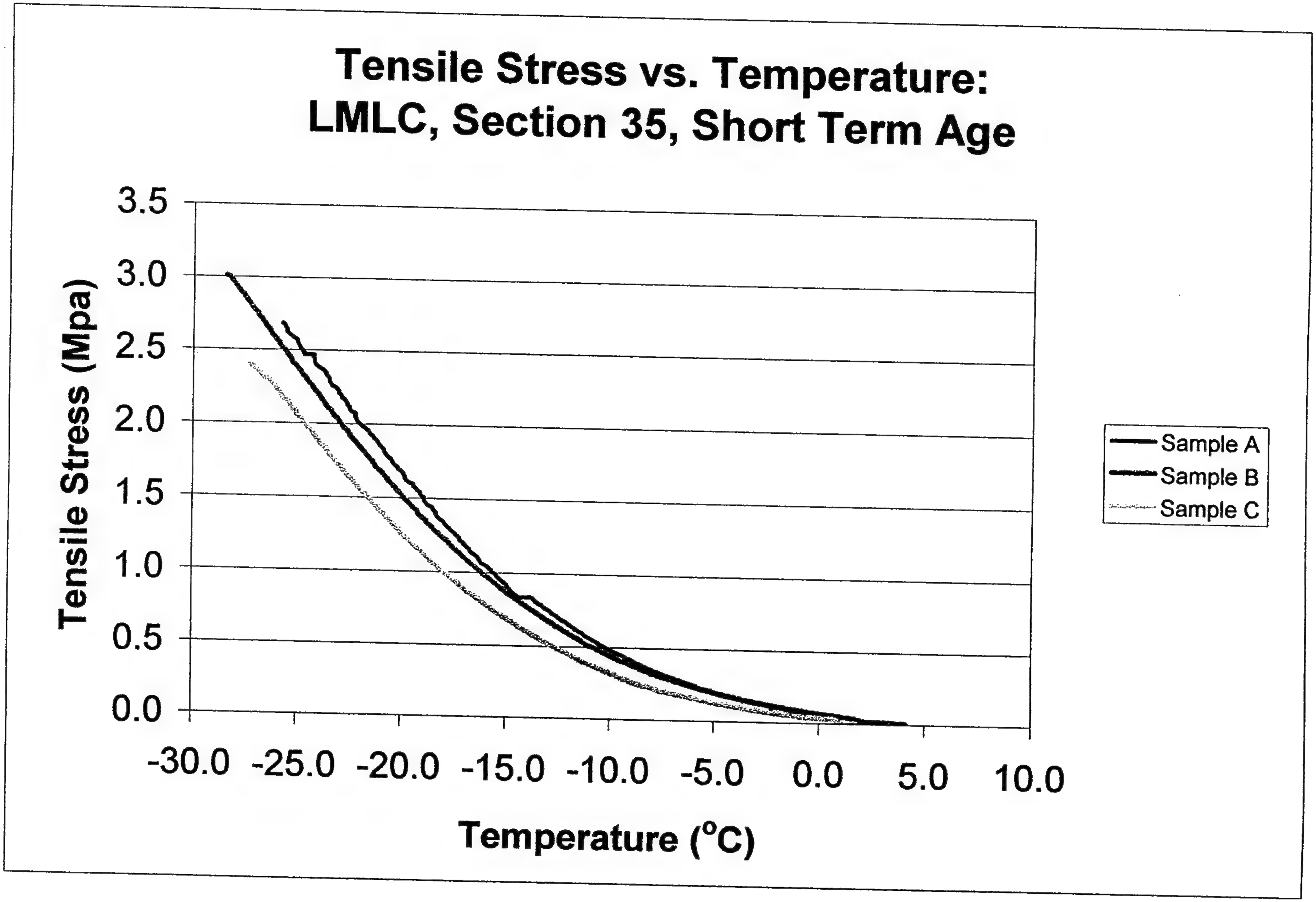

Tensile Stress vs. Temperature:
LMLC, Section 26, Short Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	12.88	1.98	287	-27.3	-17.1
	Sample B	12.63	1.92	279	-21.5	-6.6
	Sample C	12.96	2.06	298	-26.1	-14.9
Section 26 S	Mean	12.82	1.99	288	-24.9	-12.9
	Min	12.63	1.92	279	-21.5	-6.6
	Max	12.96	2.06	298	-27.3	-17.1

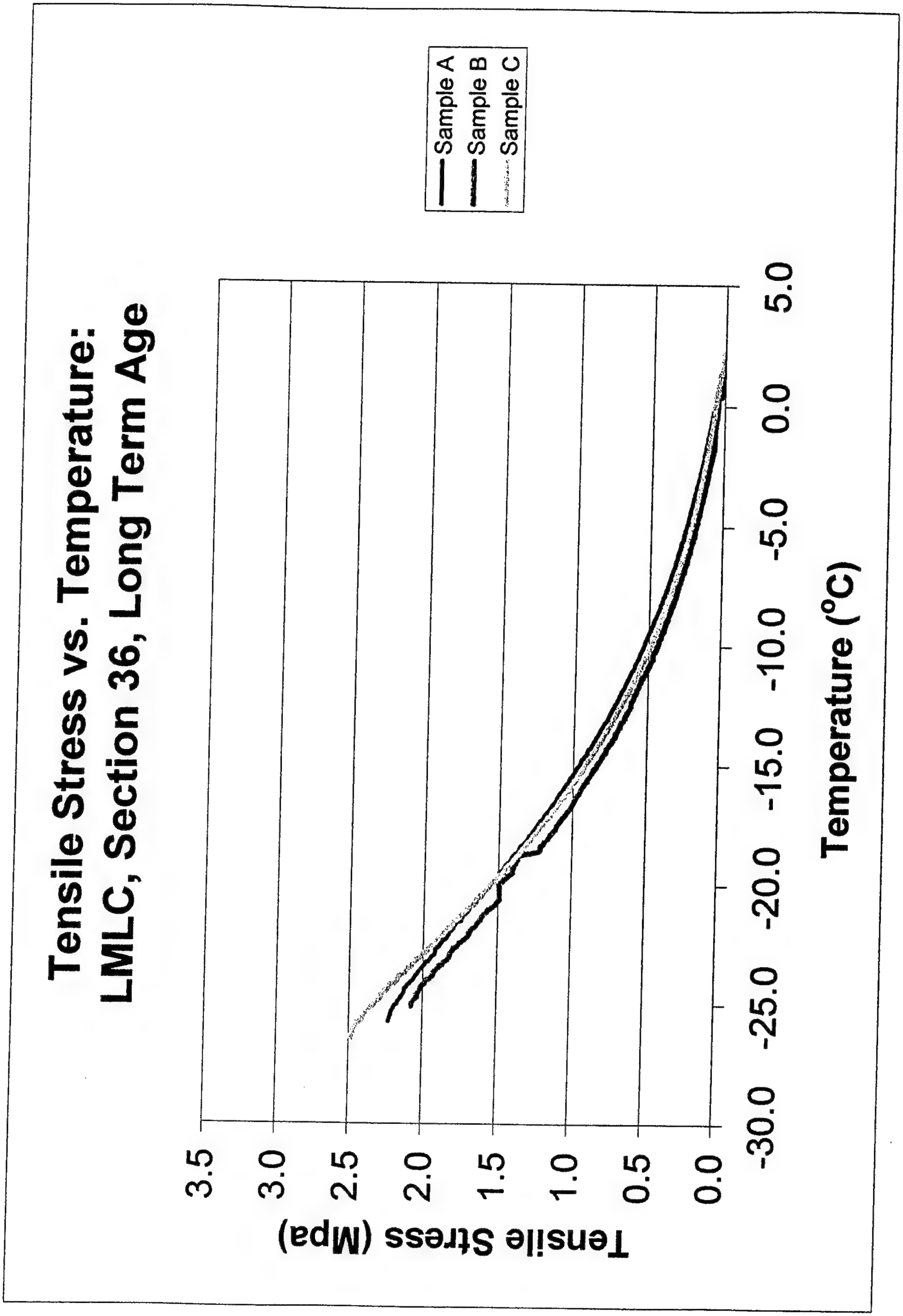


Tensile Stress vs. Temperature:
LMLC, Section 35, Long Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	8.48	2.85	413	-25.7	-14.3
	Sample B	7.66	2.56	371	-26.4	-15.6
	Sample C	8.97	2.32	337	-25.9	-14.6
Section 35 L	Mean	8.37	2.58	374	-26.0	-14.8
	Min	7.66	2.32	337	-25.7	-14.3
	Max	8.97	2.85	413	-26.4	-15.6

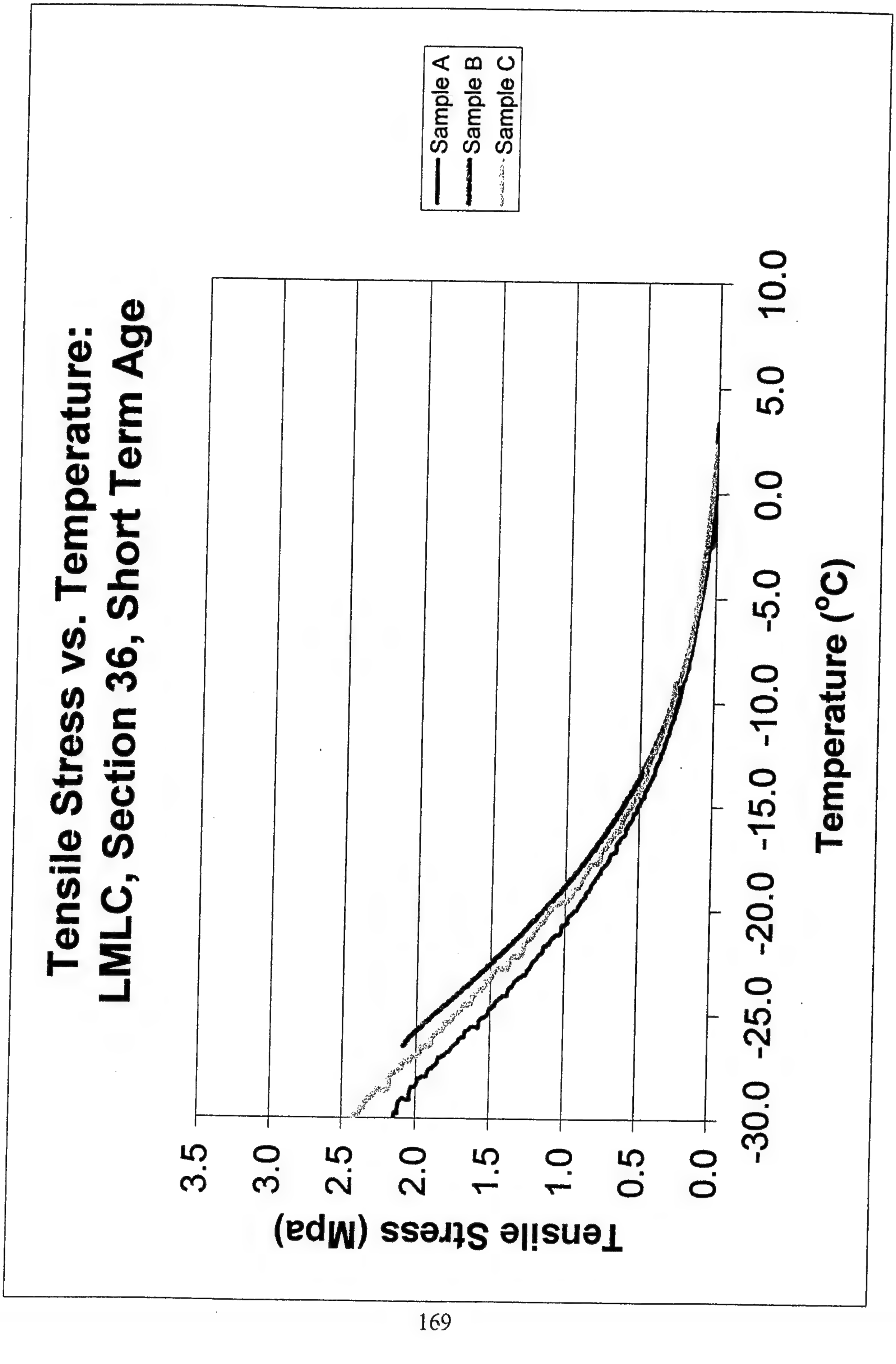

Tensile Stress vs. Temperature:
LMLC, Section 35, Short Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	7.23	2.69	389	-25.7	-14.3
	Sample B	7.67	3.01	436	-28.4	-19.2
	Sample C	8.99	2.41	349	-27.3	-17.1
Section 35 S	Mean	7.96	2.70	392	-27.1	-16.9
	Min	7.23	2.41	349	-25.7	-14.3
	Max	8.99	3.01	436	-28.4	-19.2



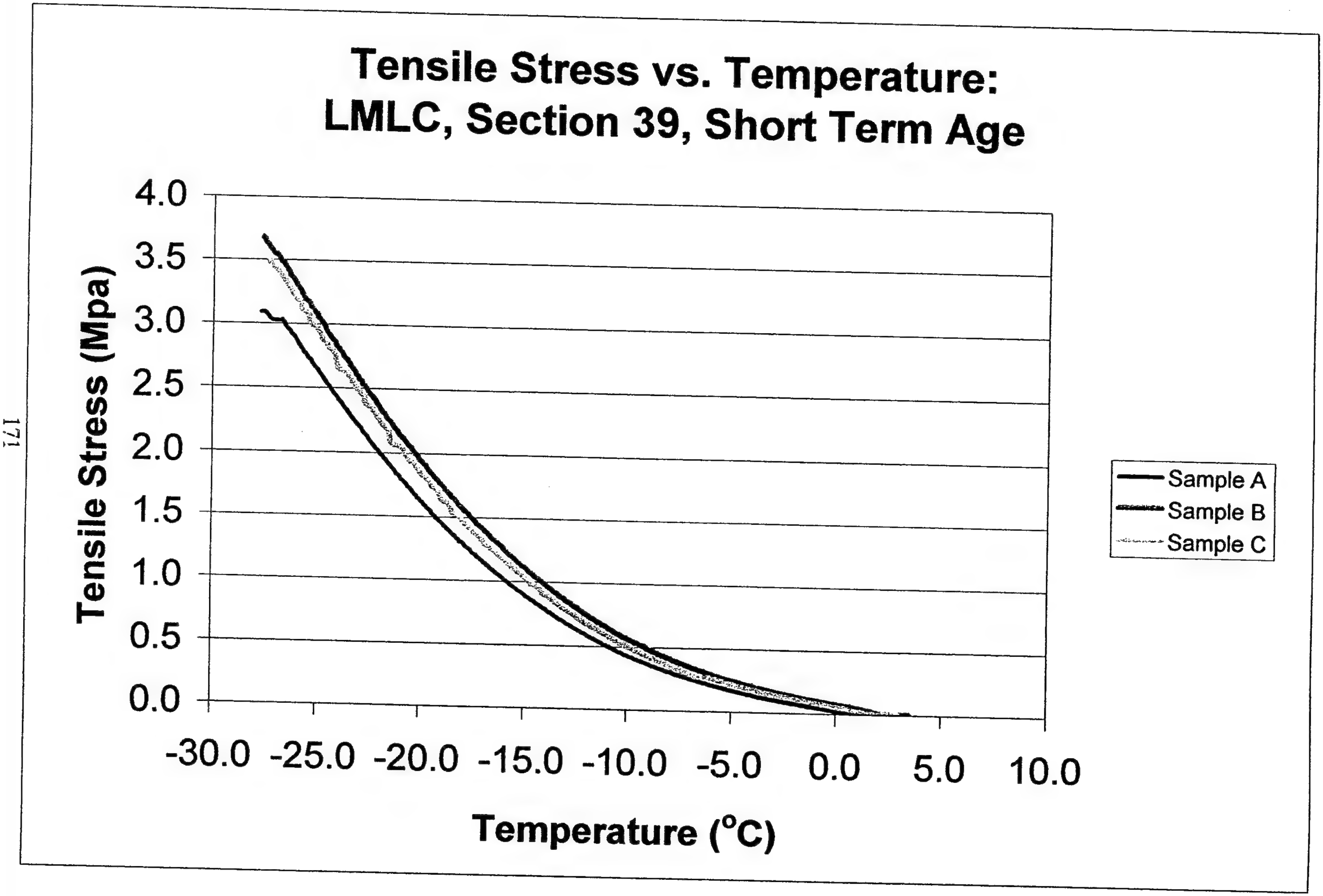
Tensile Stress vs. Temperature:
LMLC, Section 36, Long Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	12.96	2.23	324	-25.7	-14.3
	Sample B	12.54	2.08	302	-25.1	-13.2
	Sample C	11.25	2.49	360	-26.4	-15.6
Section 36 L	Mean	12.25	2.27	329	-25.8	-14.4
	Min	11.25	2.08	302	-25.1	-13.2
	Max	12.96	2.49	360	-26.4	-15.6

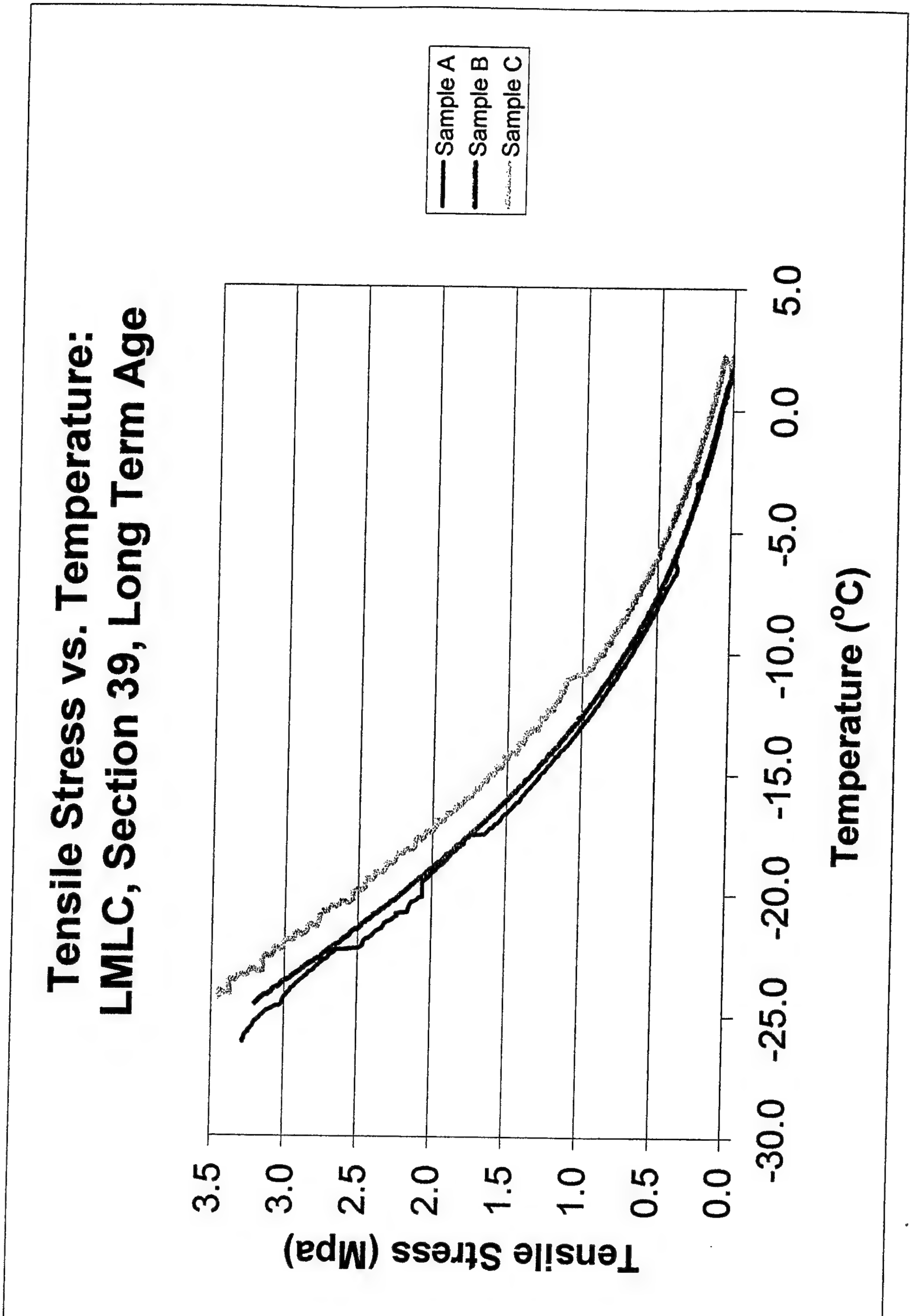


Tensile Stress vs. Temperature:
LMLC, Section 36, Short Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	12.96	2.15	311	-30.0	-22.0
	Sample B	13.00	2.09	303	-26.5	-15.8
	Sample C	11.63	2.47	358	-30.5	-22.8
Section 36 S	Mean	12.53	2.24	324	-29.0	-20.2
	Min	11.63	2.09	303	-26.5	-15.8
	Max	13.00	2.47	358	-30.5	-22.8


Tensile Stress vs. Temperature:
LMLC, Section 39, Short Term Age
Tensile Stress (Mpa)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	4.09	3.10	449	-27.7	-17.9
	Sample B	4.34	3.68	533	-27.6	-17.7
	Sample C	3.58	3.49	506	-27.4	-17.3
Section 39 S	Mean	4.00	3.42	496	-27.6	-17.6
	Min	3.58	3.10	449	-27.4	-17.3
	Max	4.34	3.68	533	-27.7	-17.9



Tensile Stress vs. Temperature:
LMLC, Section 39, Long Term Age
Tensile Stress (Mpa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-30.0
-25.0
-20.0
-15.0
-10.0
-5.0
0.0
5.0
Temperature (°C)
Sample A
Sample B
Sample C

Section	Specimen ID	Void Content (%)	Fracture Strength		Fracture Temperature	
			(MPa)	(psi)	(°C)	(°F)
Westrack LMLC	Sample A	4.04	3.28	476	-26.1	-15.0
	Sample B	4.00	3.20	464	-24.5	-12.2
	Sample C	3.83	3.45	500	-24.3	-11.7
Section 39 L	Mean	3.96	3.31	480	-25.0	-13.0
	Min	3.83	3.20	464	-24.3	-11.7
	Max	4.04	3.45	500	-26.1	-15.0

Appendix

G

Project Data Summary

Westrack Project: Summary of TSRST Data

Section	Specimen I.D.	Void Content (%)			Tensile Strength (MPa)			Tensile Strength (psi)			Fracture Temperature (°C)			Fracture Temperature (°F)			Target Asphalt Content (%)			Gradation		
		FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC
01 S	A	8.30	8.70	8.95	1.63	1.08	2.54	236.8	156.6	369.0	-22.5	-28.8	-30.1	-8.5	-19.8	-22.1	5.4	5.4	5.4	Fine	Fine	Fine
	B	10.40	8.70	8.20	1.44	1.49	1.98	208.9	216.1	287.0	-16.1	-23.6	-26.8	3.0	-10.5	-16.3	5.4	5.4	5.4	Fine	Fine	Fine
	C	10.90	9.50	8.37	1.18	1.84	1.95	171.1	266.9	282.0	-21.5	-19.6	-27.0	-6.7	-3.3	-16.5	5.4	5.4	5.4	Fine	Fine	Fine
	D	10.90	-	-	2.25	-	-	326.3	-	-	-16.5	-	-	2.3	-	-	5.4	-	-	Fine	-	-
	E	6.80	-	-	2.11	-	-	306.0	-	-	-16.9	-	-	1.6	-	-	5.4	-	-	Fine	-	-
	F	7.30	-	-	2.23	-	-	323.9	-	-	-17.3	-	-	0.9	-	-	5.4	-	-	Fine	-	-
01 L	A	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	B	-	-	8.16	-	-	2.07	-	-	301.0	-	-	-22.0	-	-	-7.6	-	-	5.4	-	-	Fine
	C	-	-	8.33	-	-	2.82	-	-	409.0	-	-	-25.3	-	-	-13.5	-	-	5.4	-	-	Fine
03 S	A	-	-	12.63	-	-	1.88	-	-	272.0	-	-	-28.3	-	-	-18.9	-	-	4.7	-	-	Fine
	B	-	-	11.75	-	-	1.55	-	-	224.0	-	-	-26.1	-	-	-15.0	-	-	4.7	-	-	Fine
	C	-	-	12.80	-	-	1.73	-	-	251.0	-	-	-28.1	-	-	-18.6	-	-	4.7	-	-	Fine
03 L	A	-	-	13.00	-	-	1.23	-	-	179.0	-	-	-21.7	-	-	-7.0	-	-	4.7	-	-	Fine
	B	-	-	12.55	-	-	1.07	-	-	155.0	-	-	-20.2	-	-	-4.3	-	-	4.7	-	-	Fine
	C	-	-	12.76	-	-	1.67	-	-	243.0	-	-	-24.9	-	-	-12.8	-	-	4.7	-	-	Fine
04 S	A	-	-	4.98	-	-	3.42	-	-	496.0	-	-	-33.6	-	-	-28.4	-	-	5.4	-	-	Fine
	B	-	-	4.98	-	-	2.66	-	-	386.0	-	-	-28.1	-	-	-18.6	-	-	5.4	-	-	Fine
	C	-	-	4.27	-	-	2.58	-	-	374.0	-	-	-25.8	-	-	-14.4	-	-	5.4	-	-	Fine
04 L	A	-	-	4.98	-	-	3.29	-	-	478.0	-	-	-25.9	-	-	-14.7	-	-	5.4	-	-	Fine
	B	-	-	4.73	-	-	2.97	-	-	[illegible]	-	-	-24.4	-	-	-12.0	-	-	5.4	-	-	Fine
	C	-	-	3.93	-	-	3.42	-	-	495.0	-	-	-25.1	-	-	-13.1	-	-	5.4	-	-	Fine
17 S	A	-	-	12.67	-	-	2.07	-	-	301.0	-	-	-27.4	-	-	-17.3	-	-	5.4	-	-	Fine
	B	-	-	11.88	-	-	1.90	-	-	275.0	-	-	-30.1	-	-	-22.2	-	-	5.4	-	-	Fine
	C	-	-	11.85	-	-	1.72	-	-	249.0	-	-	-27.9	-	-	-18.2	-	-	5.4	-	-	Fine
17 L	A	-	-	11.75	-	-	1.95	-	-	284.0	-	-	-26.8	-	-	-16.2	-	-	5.4	-	-	Fine
	B	-	-	12.81	-	-	1.90	-	-	276.0	-	-	-25.9	-	-	-14.6	-	-	5.4	-	-	Fine
	C	-	-	12.60	-	-	1.65	-	-	239.0	-	-	-25.8	-	-	-14.5	-	-	5.4	-	-	Fine
18 S	A	-	-	4.04	-	-	2.69	-	-	390.0	-	-	-28.5	-	-	-19.3	-	-	6.1	-	-	Fine
	B	-	-	4.80	-	-	3.38	-	-	491.0	-	-	-29.3	-	-	-20.7	-	-	6.1	-	-	Fine
	C	-	-	4.93	-	-	3.17	-	-	460.0	-	-	-27.1	-	-	-16.7	-	-	6.1	-	-	Fine
18 L	A	-	-	4.67	-	-	1.98	-	-	287.0	-	-	-19.0	-	-	-2.3	-	-	6.1	-	-	Fine
	B	-	-	4.84	-	-	3.72	-	-	539.0	-	-	-26.4	-	-	-15.6	-	-	6.1	-	-	Fine
	C	-	-	4.00	-	-	3.13	-	-	454.0	-	-	-24.2	-	-	-11.6	-	-	6.1	-	-	Fine
24 S	A	4.50	4.50	-	2.88	2.00	-	417.7	290.1	-	-22.1	-18.2	-	-7.8	-0.8	-	5.7	5.7	-	Coarse	Coarse	-
	B	5.00	5.00	-	2.96	2.09	-	429.3	303.1	-	-21.5	-23.9	-	-6.7	-11.0	-	5.7	5.7	-	Coarse	Coarse	-
	C	3.90	5.20	-	3.10	2.53	-	449.6	366.9	-	-26.1	-21.8	-	-15.0	-7.2	-	5.7	5.7	-	Coarse	Coarse	-
25 S	A	2.50	2.50	4.67	2.86	2.74	3.02	414.8	397.4	439.0	-19.2	-21.8	-27.1	-2.6	-7.2	-16.8	6.4	6.4	6.4	Coarse	Coarse	Coarse
	B	2.30	3.00	4.71	2.78	3.08	2.89	403.2	446.7	420.0	-21.8	-22.8	-26.7	-7.2	-9.0	-16.1	6.4	6.4	6.4	Coarse	Coarse	Coarse
	C	3.10	3.60	5.00	3.00	1.81	3.15	435.1	262.5	456.0	-22.8	-25.9	-26.9	-9.0	-14.6	-16.4	6.4	6.4	6.4	Coarse	Coarse	Coarse
25 L	A	-	-	3.91	-	-	2.79	-	-	404.0	-	-	-23.1	-	-	-9.5	-	-	6.4	-	-	Coarse
	B	-	-	4.25	-	-	3.34	-	-	484.0	-	-	-25.8	-	-	-14.4	-	-	6.4	-	-	Coarse
	C	-	-	3.91	-	-	2.83	-	-	410.0	-	-	-32.4	-	-	-26.3	-	-	6.4	-	-	Coarse

Westrack Project: Summary of TSRST Data

Section	Specimen I.D.	Void Content			Tensile Strength						Fracture Temperature						Target Asphalt Content			Gradation		
		(%)			(MPa)			(psi)			(°C)			(°F)			(%)					
		FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC	FMFC	FMLC	LMLC
26 S	A	8.20	8.70	[illegible]	2.63	[illegible]	2.56	343.7	97.2	287.0	-22.5	-26.8	-29.3	-6.7	-0.9	-17.1	5.6	5.6	5.6	Coarse	Coarse	Coarse
	B	8.40	7.30	12.63	2.28	0.90	1.92	330.7	130.5	279.0	-20.3	-23.1	-21.5	-4.5	-9.6	-6.6	5.0	5.0	5.0	Coarse	Coarse	Coarse
	C	8.60	6.70	12.96	2.41	0.26	2.06	349.5	37.7	298.0	-20.7	-13.3	-26.1	-5.3	8.1	-14.9	5.0	5.0	5.0	Coarse	Coarse	Coarse
26 L	A	-	-	12.43	-	-	2.08	-	-	301.0	-	-	-24.7	-	-	-12.5	-	-	5.0	-	-	Coarse
	B	-	-	12.88	-	-	1.89	-	-	275.0	-	-	-24.2	-	-	-11.6	-	-	5.0	-	-	Coarse
	C	-	-	12.26	-	-	2.19	-	-	318.0	-	-	-25.6	-	-	-14.1	-	-	5.0	-	-	Coarse
35 S	A	8.10	8.30	7.23	1.76	2.05	2.69	255.3	297.3	389.0	-25.5	-22.5	-25.7	-13.9	-8.5	-14.3	5.7	5.7	5.7	Coarse	Coarse	Coarse
	B	8.10	7.50	7.87	2.11	2.23	3.01	306.0	323.4	436.0	-25.8	-21.7	-28.4	-14.4	-7.1	-19.2	5.7	5.7	5.7	Coarse	Coarse	Coarse
	C	7.80	7.50	8.99	1.99	2.15	2.41	288.6	311.8	349.0	-26.1	-22.3	-27.3	-15.0	-8.1	-17.1	5.7	5.7	5.7	Coarse	Coarse	Coarse
35 L	A	-	-	8.48	-	-	2.85	-	-	413.0	-	-	-25.7	-	-	-14.3	-	-	5.7	-	-	Coarse
	B	-	-	7.86	-	-	2.56	-	-	371.0	-	-	-26.4	-	-	-15.6	-	-	5.7	-	-	Coarse
	C	-	-	8.97	-	-	2.32	-	-	337.0	-	-	-25.9	-	-	-14.6	-	-	5.7	-	-	Coarse
36 S	A	12.40	8.00	12.96	1.15	1.87	2.15	166.8	271.2	311.0	-26.5	-20.8	-30.0	-15.7	-5.4	-22.0	5.7	5.7	5.7	Coarse	Coarse	Coarse
	B	12.50	7.20	13.00	1.23	2.25	2.09	178.4	326.3	303.0	-24.8	-21.4	-26.5	-12.6	-6.5	-15.8	5.7	5.7	5.7	Coarse	Coarse	Coarse
	C	12.50	7.50	11.63	1.10	2.47	2.47	159.5	358.2	358.0	-35.0	-21.6	-30.5	-31.0	-6.9	-22.8	5.7	5.7	5.7	Coarse	Coarse	Coarse
36 L	A	-	-	12.96	-	-	2.23	-	-	324.0	-	-	-25.7	-	-	-14.3	-	-	5.7	-	-	Coarse
	B	-	-	12.54	-	-	2.08	-	-	302.0	-	-	-25.1	-	-	-13.2	-	-	5.7	-	-	Coarse
	C	-	-	11.25	-	-	2.49	-	-	360.0	-	-	-26.4	-	-	-15.6	-	-	5.7	-	-	Coarse
37 S	A	9.50	7.00	-	1.58	2.17	-	229.2	314.7	-	-23.6	-23.6	-	-10.5	-10.5	-	6.4	6.4	-	Coarse	Coarse	-
	B	8.30	8.20	-	2.14	2.10	-	310.4	304.6	-	-25.1	-23.6	-	-13.2	-10.5	-	6.4	6.4	-	Coarse	Coarse	-
	C	9.60	7.50	-	1.70	1.94	-	240.0	281.4	-	-24.4	-21.0	-	-11.9	-5.8	-	6.4	6.4	-	Coarse	Coarse	-
38 S	A	6.90	8.70	-	2.59	2.75	-	375.6	398.9	-	-26.8	-21.0	-	-16.2	-5.8	-	5.0	5.0	-	Coarse	Coarse	-
	B	6.80	8.90	-	2.90	2.62	-	420.6	380.0	-	-27.4	-20.1	-	-17.3	-4.2	-	5.0	5.0	-	Coarse	Coarse	-
	C	8.10	6.70	-	2.14	2.79	-	310.4	404.7	-	-26.1	-22.7	-	-15.0	-8.9	-	5.0	5.0	-	Coarse	Coarse	-
39 S	A	4.20	8.20	4.09	2.62	1.60	3.10	380.0	232.1	449.0	-24.6	-21.5	-27.7	-12.3	-6.7	-17.9	5.7	5.7	5.7	Coarse	Coarse	Coarse
	B	4.30	7.90	4.34	3.01	1.64	3.68	436.6	237.9	533.0	-23.6	-21.0	-27.6	-10.5	-5.8	-17.7	5.7	5.7	5.7	Coarse	Coarse	Coarse
	C	3.00	8.20	3.58	3.32	1.73	3.49	481.5	250.9	506.0	-25.4	-21.1	-27.4	-13.7	-6.0	-17.3	5.7	5.7	5.7	Coarse	Coarse	Coarse
39 L	A	-	-	4.04	-	-	3.28	-	-	476.0	-	-	-26.1	-	-	-15.0	-	-	5.7	-	-	Coarse
	B	-	-	4.00	-	-	3.20	-	-	464.0	-	-	-24.5	-	-	-12.2	-	-	5.7	-	-	Coarse
	C	-	-	3.83	-	-	3.45	-	-	500.0	-	-	-24.3	-	-	-11.7	-	-	5.7	-	-	Coarse